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The Anaconda Company, Anaconda, Montana October 1 - December 9, 1976

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A field study was conducted during October 1 to December 8, 1976 to measure parameters of the effluent plume of The Anaconda Company's copper smelter, Anaconda, Montana. Plume parameters were observed with a helicopter-borne air quality monitoring system. This data report presents plume heights, plume horizontal and vertical dispersion, and plume centerline concentration, and low-altitude sulfur dioxide concentrations over areas of plume impaction. Nephelometer and SO_2 data have been adjusted to account for instrument response times.

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AIRBORNE MEASUREMENTS OF A COPPER SMELTER PLUME IN MONTANA

The Anaconda Company, Anaconda, Montana
October 1 - December 9, 1976

by

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FOREWORD

Protection of the environment requires effective regulatory actions which are based on sound technical and scientific information. This information must include the quantitative description and linking of pollutant sources, transport mechanisms, interactions, and resulting effects on man and his environment. Because of the complexities involved, assessment of specific pollutants in the environment requires a total systems approach which transcends the media of air, water, and land. The Environmental Monitoring and Support Laboratory-Las Vegas contributes to the formation and enhancement of a sound monitoring data base for exposure assessment through programs designed to:

- develop and optimize systems and strategies for monitoring pollutants and their impact on the environment
- demonstrate new monitoring systems and technologies by applying them to fulfill special monitoring needs of the Agency's operating programs

This report presents the results of helicopter measurements taken to determine the geometry of the plume of The Anaconda Company's copper smelter at Anaconda, Montana. These data were collected as input to mathematical models used to predict ambient concentrations in the Anaconda area. In addition, this report represents a significant contribution to the effort to gain more insight into rates of diffusion on complex terrain. The Air Quality Branch of the Environmental Monitoring and Support Laboratory, Las Vegas may be contacted for further information as to the availability of these data.

George B. Morgan

George B. Morgan
Director
Environmental Monitoring and Support Laboratory
Las Vegas

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LIST OF ABBREVIATIONS

ABBREVIATIONS

AGL	Above ground level
BRKN	Broken (5/8 to 7/8 cloud cover)
B_{scat}	Total light scattering
C	Celsius
CLM	Calm winds
EMSL-LV	Environmental Monitoring and Support Laboratory-Las Vegas
EPA	U.S. Environmental Protection Agency
K	Kelvin
kg	Kilogram
km	Kilometer
m	Meter
min	Minute
MOD	Monitoring Operations Division
MSL	Mean Sea Level
MST	Mountain Standard Time
N	Neutral
OAT	Outside Air Temperature
OVC	Overcast (8/8 cloud cover)
ppm	Parts per million
s	Seconds
SCT	Scattered (1/8 to 4/8 cloud cover)
THN	Thin (cloud layer less than opaque)
TST	True solar time

LIST OF SYMBOLS

SYMBOLS	
μg	Microgram
Po	Sea level pressure (mb)
Γd	Dry adiabatic lapse rate (^{o}C/m)
R	Gas constant
S	Stable
τ	Time constant
χ_{in}	Input concentration
χ_{max}	Centerline concentration
χ_{out}	Output concentration
σ_y	Horizontal dispersion coefficients
σ_z	Vertical dispersion coefficient
X	Obscured
W	Indefinite
Z	Height above ground

INTRODUCTION

The State of Montana and The Anaconda Company have been monitoring air quality in the locale of the Anaconda copper smelter for years using a network of sulfur dioxide (SO_2) monitors. Violations of the primary and secondary SO_2 standards have been recorded. The amount of control required has been estimated using a mathematical dispersion model and the data from the two monitoring networks. The representativeness of the data from the fixed network stations to portray maximum ambient concentrations has been questioned on the basis of station locations. In addition, the magnitude and frequency of violations of the air quality standards projected for areas which have no monitoring stations have been sharply debated. The mountainous area south and west of the smelter is of major concern. The probability that the plume will strike the ground in this area is increased because of the high ground elevations relative to the stack height. No SO_2 monitors are located in these remote areas.

In response to a request from the U.S. Environmental Protection Agency (EPA) Regional Administrator for Region VIII, the Monitoring Operations Division (MOD) of the Environmental Monitoring and Support Laboratory-Las Vegas (EMSL-LV) conducted a field study between October 1, 1976 and January 31, 1977, to characterize the plume of The Anaconda Company smelter in Anaconda, Montana. During the period October 1 to December 8, 1976, an instrumented EMSL-LV helicopter was deployed to measure plume parameters for comparison with model calculations. The parameters of interest were plume height, horizontal and vertical plume spread, and concentration of SO_2 at the plume centerline and near points of surface contact.

The helicopter-borne air quality monitoring system measured concentrations of SO_2, nitric oxide, oxides of nitrogen, ozone, aerosol light scattering (nephelometer), temperature, dewpoint, and location. The SO_2 and nephelometer data have been adjusted for instrument response times.

A helicopter-transportable ground SO_2 monitor was developed and used to measure SO_2 concentrations in remote areas impacted by the smelter plume. Double theodolite upper-level wind measurements were taken over the 4-month period. The results of the ground SO_2 measurements are contained in an EMSL-LV report (van Ee, 1978). The wind data are available at this office.

SUMMARY

The EMSL-LV conducted a field study between October 1, 1976 and January 31, 1977, to characterize the plume of The Anaconda Company copper smelter in Anaconda, Montana. During the period October 1 to December 8, 1976, an instrumented EMSL-LV helicopter was deployed to measure plume parameters for input to mathematical models. The parameters of interest included plume height-of-rise, horizontal and vertical plume spread, and concentrations of SO_2 at the plume centerline and near points of ground contact for input to mathematical models.

The helicopter-borne air quality monitoring system measured concentrations of SO_2, nitric oxide, oxides of nitrogen, ozone, aerosol light scattering (nephelometer), dewpoint and temperature, and location. This system was installed in a Sikorsky S-58 helicopter. The SO_2 and nephelometer data have been adjusted to account for instrument response times.

In addition, a helicopter-transportable ground SO_2 monitor was developed and was used to measure SO_2 concentrations in remote areas impacted by the smelter plume (van Ee 1978). Double theodolite upper-level wind data were obtained for the 4-month period and are on file at this office.

Thirty-nine sampling missions were flown by the S-58 during the field study period. Nine of these were aborted due to instrument malfunction, aircraft problems, or adverse weather conditions. The coefficient, σ_y, determined from multiple transects through the plume at a given distance for a given mission are shown in Figure 1. Both nephelometer and SO_2 data are reported. As many as 19 transects are represented by each point. The data are adjusted to a hypothetical 3-minute sampling period. The Pasquill-Gifford-Turner (Turner, 1969) dispersion coefficients have been included for comparison.

An attempt was initially made to separate the stable and neutral stability cases as determined from temperature soundings. Due to the complexity of the terrain and other factors, such a stratification proved to be insignificant. Stratification of the data was made based on wind direction and the character of temperature inversions (See Appendix E).

The large scatter of the thermally stratified dispersion coefficients suggests that the amount of turbulence associated with flows having various velocities in this highly complex terrain is important in determining plume dispersion. For this reason, each set of observations is nearly unique and should be treated as such when applying them to mathematical models. The least squares fit of all the data suggests that, in general, more rapid

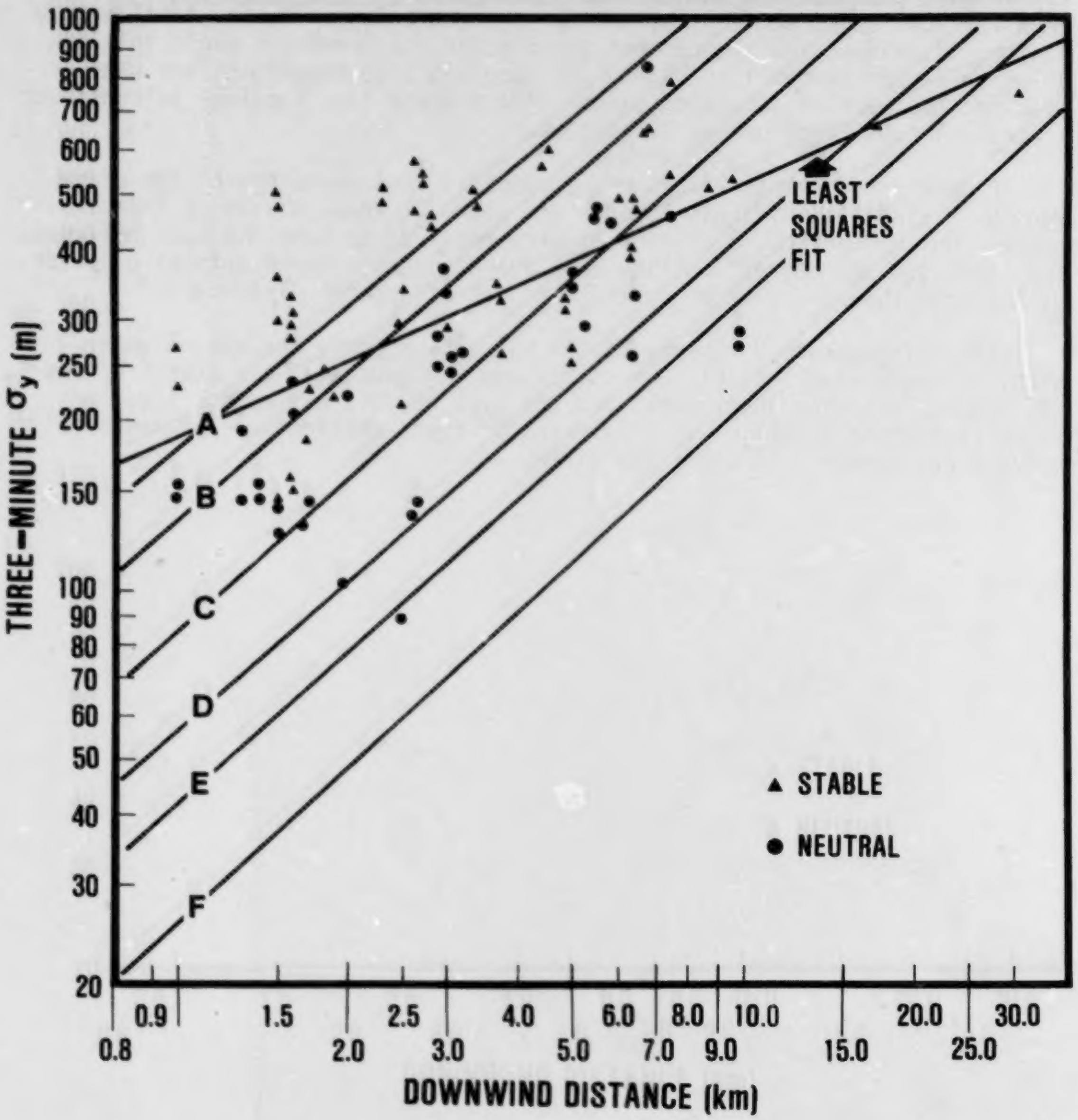

Figure 1. Horizontal Diffusion Coefficients vs. Distance.

dilution than might be expected occurs near the stack. This has been observed previously (Fanak and Turner, 1976).

Figure 2 summarizes the vertical dispersion coefficients, σ_z, computed from vertical cross sections of maximum concentrations. Again, considerable scatter is evident for the reasons given above. A trend for rapid initial dilution in the vertical is noted. No sampling time adjustment has been made for the vertical cross sections. The average time required to construct a vertical cross section was 33 minutes.

Figure 3 represents values of σ_z computed from soundings of the plume made by flying tight spirals through the plume at known distances from the stack. On the average, 3.37 minutes were required to complete each maneuver. The least squares regression line once again suggests rapid initial dilution with little further dilution in the vertical at greater distances.

Table 1 presents a summary of the missions flown. The predominant stability near stack height (S = stable and N = neutral), the status of the SO_2 and nephelometer instruments and the type of data collected, i.e., plume centerline height, σ_y, σ_z by means of cross sections, σ_z by means of spirals and upper level winds are given.

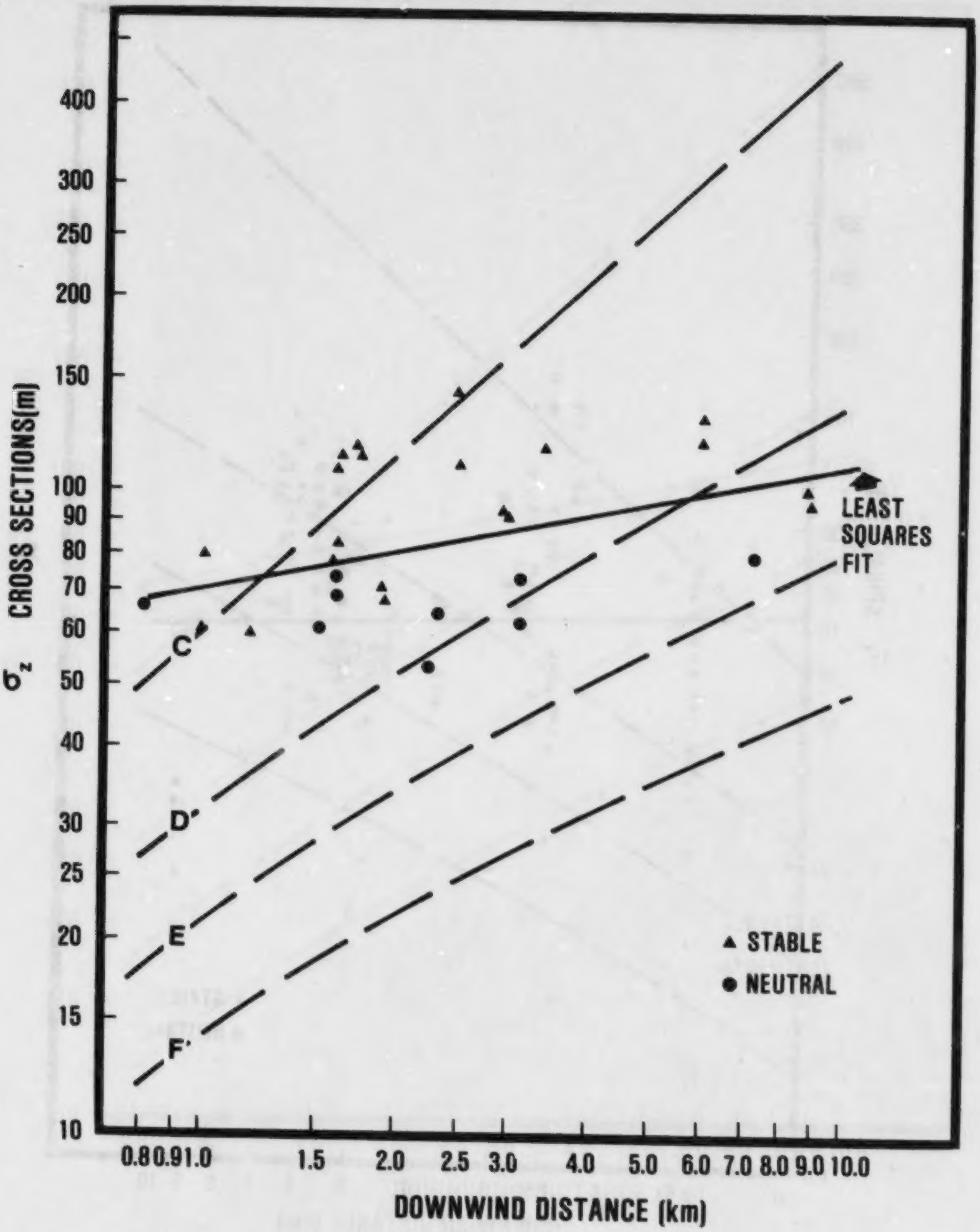

Figure 2. Vertical Diffusion Coefficients (Cross Sections) vs. Distance.

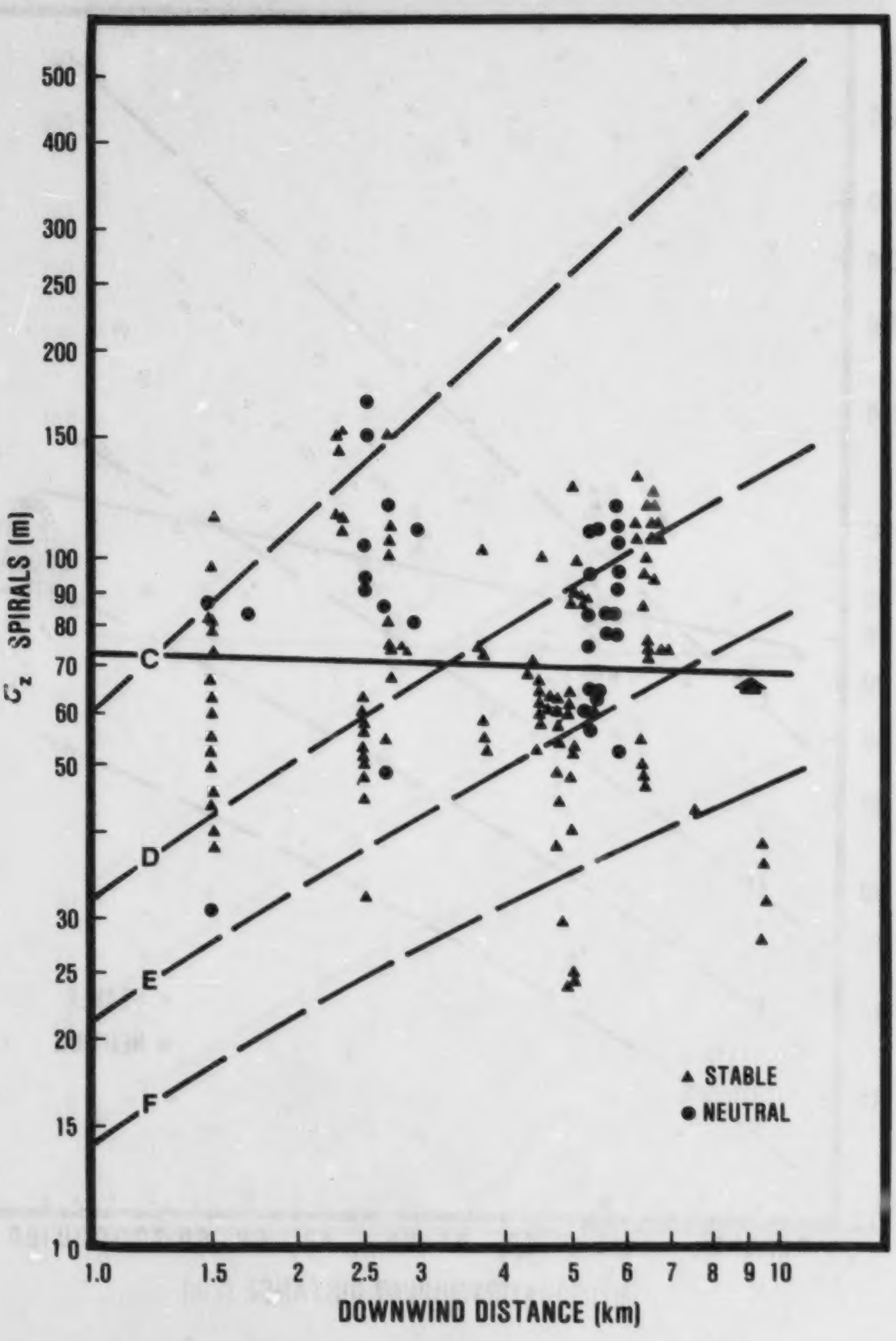

Figure 3. Vertical Diffusion Coefficients (Spirals) vs. Distance.

TABLE 1. SUMMARY OF MISSIONS

Date	Stability	SO_2	B_{scat}	Plume Height	σ_y	σ_z X-section	σ_z Spirals	Winds
10/01/76	S		X	X			X	
10/04/76	N		X	X	X		X	
10/05/76	S		X	X	X		X	X
10/07/76	S	X	X	X	X		X	X
10/08/76	S	X	X	X	X		X	X
10/12/76	S	X	X	X	X		X	X
10/13/76	S	X	X		X		X	X
10/14/76	N	X					X	X
10/19/76	S	X	X	X	X		X	X
10/20/76	S	X	X	X	X		X	X
10/21/76	S	X	X	X	X	X	X	X
10/22/76	S	X	X	X	X		X	X
10/26/76	N	X	X	X	X		X	X
10/27/76	S	X	X	X	X		X	X
10/28/76	S	X	X	X	X		X	X
10/29/76	N	X	X	X	X	X	X	X
11/01/76	N	X	X	X	X			X
11/03/76	N	X	X	X	X	X		X
11/04/76	S	X	X	X	X	X	X	X

(Continued)

TABLE 1. SUMMARY OF MISSIONS (Continued)

Date	Stability	SO_2	B_{scat}	Plume Height	σ_y	σ_z X-section	σ_z Spirals	Winds
11/05/76	N-S	X	X	X	X	X		X
11/08/76	N	X	X	X	X	X		X
11/09/76	N	X	X	X	X			X
11/10/76	S-N	X	X	X	X	X		X
11/11/76	S	X	X		X	X		X
11/12/76	S	X			X	X	X	X
11/13/76	S	X			X		X	X
11/15/76	UNK	X			X			X
11/16/77	S	X	X	X	X	X	X	X
11/17/77	S	X	X	X	X	X	X	X
12/03/77	S	X	X	X	X	X		X
12/08/77	S	X	X	X	X		X	X

RECOMMENDATIONS

- That the complexity of the terrain in the vicinity of the smelter be characterized and an attempt be made to correlate terrain to plume dispersion.

- That a permanent SO_2 monitoring station be placed on the elevated terrain to the southwest of the smoke stack.

- That all of the upper level wind data be analyzed for persistence and frequency. That these data be analyzed for directional and vertical wind shear and some attempt be made to establish correlative properties to plume dispersion.

- That the frequently observed downwash conditions be investigated and reported on separately.

- That a statistical investigation be made of the data in an attempt to optimize helicopter plume sampling techniques.

DESCRIPTION OF THE ANACONDA SMELTER

The Anaconda smelter is a primary copper smelter. It produces copper anodes from concentrates of sulfide ores, leached precipitates, and scrap.

At the time of the plume study, the smelter was operating 24 hours per day, seven days per week, with operations interrupted occasionally for maintenance. Production for this period (October 1976 through February 1977) averaged approximately 560 tons of anode copper per day. Smelting was accomplished by a reverberatory furnace (receiving approximately 20 percent of copper feed) and a fluid bed roaster - electric furnace (receiving approximately 80 percent of the copper feed). Matte from the two furnace systems was converted to blister copper by blowing in Pierce-Smith converters. Blister copper from the converters was then refined in gas-fired furnaces and then cast into anodes. Figure 4 is a block diagram which shows the operation and flue gas flows.

The sulfur charging rate into the smelter averaged approximately 5.5×10^5 kg per day during the study period. Small amounts of sulfur left the smelter in the slag, as fugitive emissions and as SO_x emissions from the acid plant stack. The large majority of sulfur was emitted as SO_2 in flue gas. The flue system conveyed most of these gases to the main stack except for a small amount which was diverted into the acid plant when this unit was operating. Most of the flue gas diverted into the acid plant came from the flow from the converter hoods. When the acid plant was operating, the volume diverted was approximately 34 m^3/s. The actual sulfur intake varied with the SO_2 content of the flue gas. The average intake of sulfur into the acid plant was approximately 3,270 kg/hr.

TABLE 2. SOURCE CHARACTERISTICS[1]

Source:	Main Stack
Stack Height:	178 m, the stack is on a hill 203 m above the valley floor to the east.
Stack Diameter:	18.3 m
Exit Velocity[2]:	1.92 to 2.52 m/s
Flow Rate[3]:	505 to 661 m^3/s
Exit Temperature[4]:	337 to 370° K
SO_2 Emission Rate:	0.86 to 10.83 kg/s
Stack Concentration[5]:	1.7×10^6 to 16.4×10^6 $\mu g/m^3$

[1] Information furnished by Region VIII, U.S. Environmental Protection Agency.

[2] Based on stack area and flow rate.

[3] Measured at 1000 MST daily.

[4] Measured 41.14 m below stack top.

[5] Based on exit velocity and emission rates.

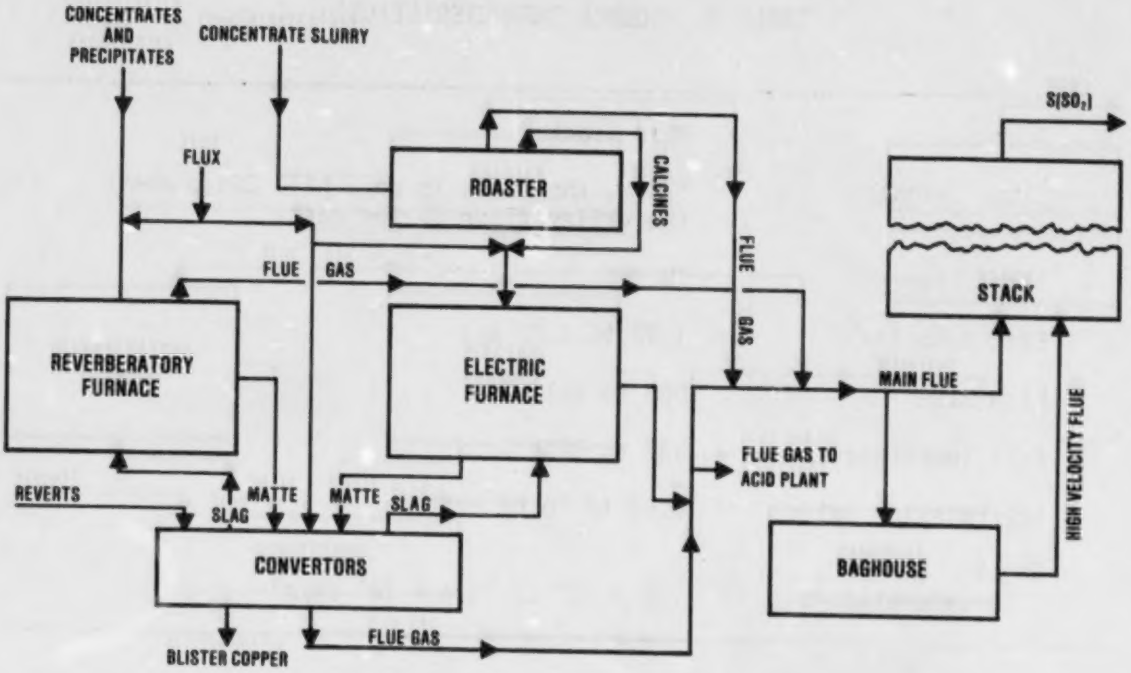

Figure 4. Smelting Process, Anaconda, Montana.

DESCRIPTION OF DATA COLLECTION AND PROCESSING

A Sikorsky S-58 helicopter was used for in-plume measurements (See Figure 5). Its sampling speed was 60 knots (KTS), its cruising range was approximately 4 hours and its operational ceiling was approximately 2750 m mean sea level (MSL). The helicopter was instrumented to measure the following parameters (instrument designation): ozone (Rem 216 B), nitric oxide and oxides of nitrogen (Monitor Labs ML8440)* and sulfur dioxide (TECO-43). Aerosol light scattering was measured with an integrating nephelometer, B_{scat}, (MRI 1550). Measurements were also made of temperature and dewpoint, (Cambridge CS-137), position (Collins DME-40) and altitude (Computer Instruments Corporation 8000). Position was determined by continuous triangulation using two air navigation beacons. In addition, magnetic heading was recorded. Figure 6 is a block diagram of the instrument package. Analog and digital voltages were processed by a data acquisition system (Monitor Labs ML 7200) at a selected rate of scan either 1 or 2 seconds.

The data system converts the output voltages to BCD characters recorded on 7-track magnetic tape (Cipher 70). The magnetic tape was then processed by a digital computer and a printout of calibrated engineering units was obtained. In addition, any four analog outputs could be recorded on a strip chart recorder. Calibration procedures are described in Appendix J.

In addition to the routine adjustments that were applied to output data based on calibration and span of the instruments, two other considerations were made when processing the data. These were instrument response and averaging times. A complete description of the data adjustment for instrument response may be found in Appendix B and for sampling time in Appendix C. Plume parameters and horizontal and vertical dispersion coefficients were determined by application of the method of moments as outlined in Appendix D.

The following types of missions were flown:

1. Flights to dimensionalize the plumes. These consisted of tight spiral descents through the plume at known distances from the stack to determine the vertical extent of the plume and the height of the plume centerline. These were immediately followed by one or more transects at centerline height to measure the plume's lateral extent and to determine

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*Although O_3, NO and NO_x were measured, no measurable amounts of oxides of nitrogen, and no significant O_3 deficiency was noted within the plume.

the centerline concentration. This technique is preferable for the more unstable or very stable conditions as it takes less time than the other maneuvers. It is also more applicable at greater distances where the diameter of the spiral would not introduce as large a proportional variation in the distance from the stack.

2. Helicopter flights to obtain data with which to construct vertical cross sections of the plume. These flights consisted of a series of transects through the plume, normal to the wind flow and over a given path, at incremented altitudes (usually 30 m) in order to determine the horizontal and vertical distribution of the various pollutants.

3. Low altitude helicopter measurements to determine near ground level concentrations of SO_2 during the periods when the plume was observed impacting upon the surface.

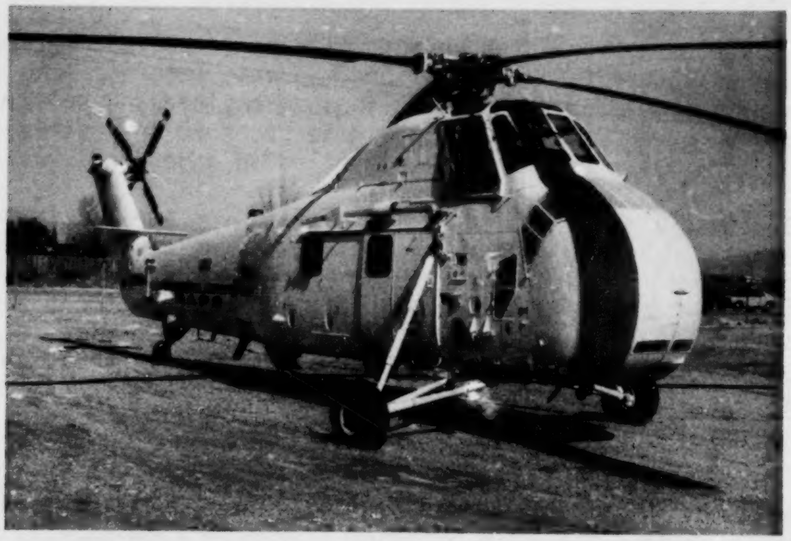

Figure 5. Sikorsky S-58 helicopter.

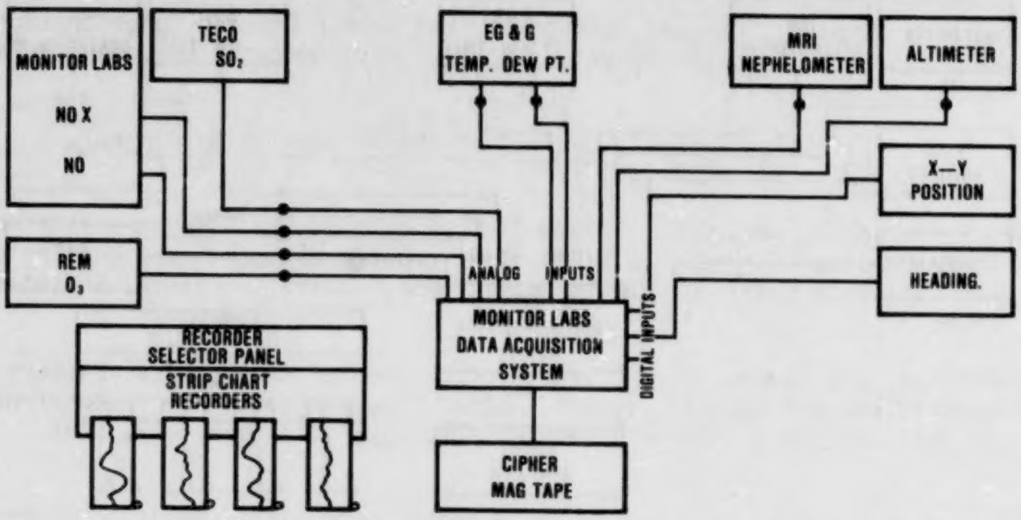

Figure 6. Helicopter Instrumentation.

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APPENDIX A. DESCRIPTIONS AND RESULTS OF FLIGHTS

Included in this appendix are descriptions of each flight, a summary of the results of each flight, a map showing the location of sampling, photographs of the plume, and temperature (OAT) and dewpoint (DPT) profiles. Included with the temperature profiles are stack height and the dry adiabatic lapse rate, Γ_d. Heights are given in meters above mean sea level (m MSL). Measurements were made of both SO_2 and particulate distribution (B_{scat}). Omissions indicate that the data are not available.

The following format is followed for each flight.

1. Weather observations: taken by FAA personnel at the Silver Bow County Airport, Butte, Montana. The following data are presented.

   a. Time (MST)
   b. Cloud Height (hundreds of feet above surface) HI indicates cirroform clouds
   c. Cloud cover
   d. Wind direction (direction wind blowing from, degrees true north)
   e. Wind speed (knots)

The following abbreviations are used:

   a. CLR = clear (less than 1/8 cloud cover)
   b. SCT = scattered (1/8 to 4/8 cloud cover)
   c. BRKN = broken (5/8 to 7/8 cloud cover)
   d. OVC = overcast (8/8 cloud cover)
   e. THN = thin
   f. CLM = calm wind

2. Plant emissions, SO_2: Time (MST) followed by SO_2 emissions in micrograms per seconds (μg/s).

3. Centerline height/distance/concentration: Height of plume centerline (m MSL)/distance from the stack (km)/concentration at plume centerline, SO_2 (ppm).

4. Three-minute σ_y: Average value or σ_y adjusted to a 3-minute sampling period obtained by making one or more transects through the plume at a given distance from the stack. This is followed by the type of instrument used: B_{scat} or SO_2. The following format is used:

Average values of σ_y(m)/standard deviation of the σ_ys(m)/number of measurements considered in determining the average/distance from the stack (km).

5. σ_z values as determined from cross sections (m)/time required to construct cross section (minutes)/distance from the stack (km).

6. σ_z values as determined from spirals through the plume. The format is the same as #5.

7. Winds aloft as determined from pibal measurements. The following format was used: Time (MST)/height (m MSL)/direction (True North)/speed (m/s).

October 1, 1976 0724-0940 MST

Stable conditions were noted at stack height throughout the mission. Spirals were made through the plume at 2.7 km from the stack. These were followed by transects through the plume at the height of plume centerline. The SO_2 instrument was not operational. No wind measurements were made.

TABLE A-1
SUMMARY OF MISSION, OCTOBER 1, 1976

1. Butte Weather: 0800 150 SCT 130/03
   1100 150 THN SCT 330/03
2. Centerline Height/ Distance/ Concentration: ≈2200 m MSL/ 2.7 km/----
3. Three-minute σ_y, B_{scat}: 143 m/ 25 m/ 3 cases/ 2.7 km
4. σ_z, Spiral, B_{scat}: 112 m/ 4.2 min/ 2.7 km
   67 m/ 3.8 min/ 2.7 km
   54 m/ 2.0 min/ 2.7 km
   74 m/ 3.0 min/ 2.7 km
   74 m/ 3.8 min/ 2.7 km
   151 m/ 5.2 min/ 2.7 km
   100 m/ 4.2 min/ 2.7 km
   80 m/ 3.3 min/ 2.7 km
   82 m/ 4.6 min/ 2.7 km
   105 m/ 3.7 min/ 2.7 km

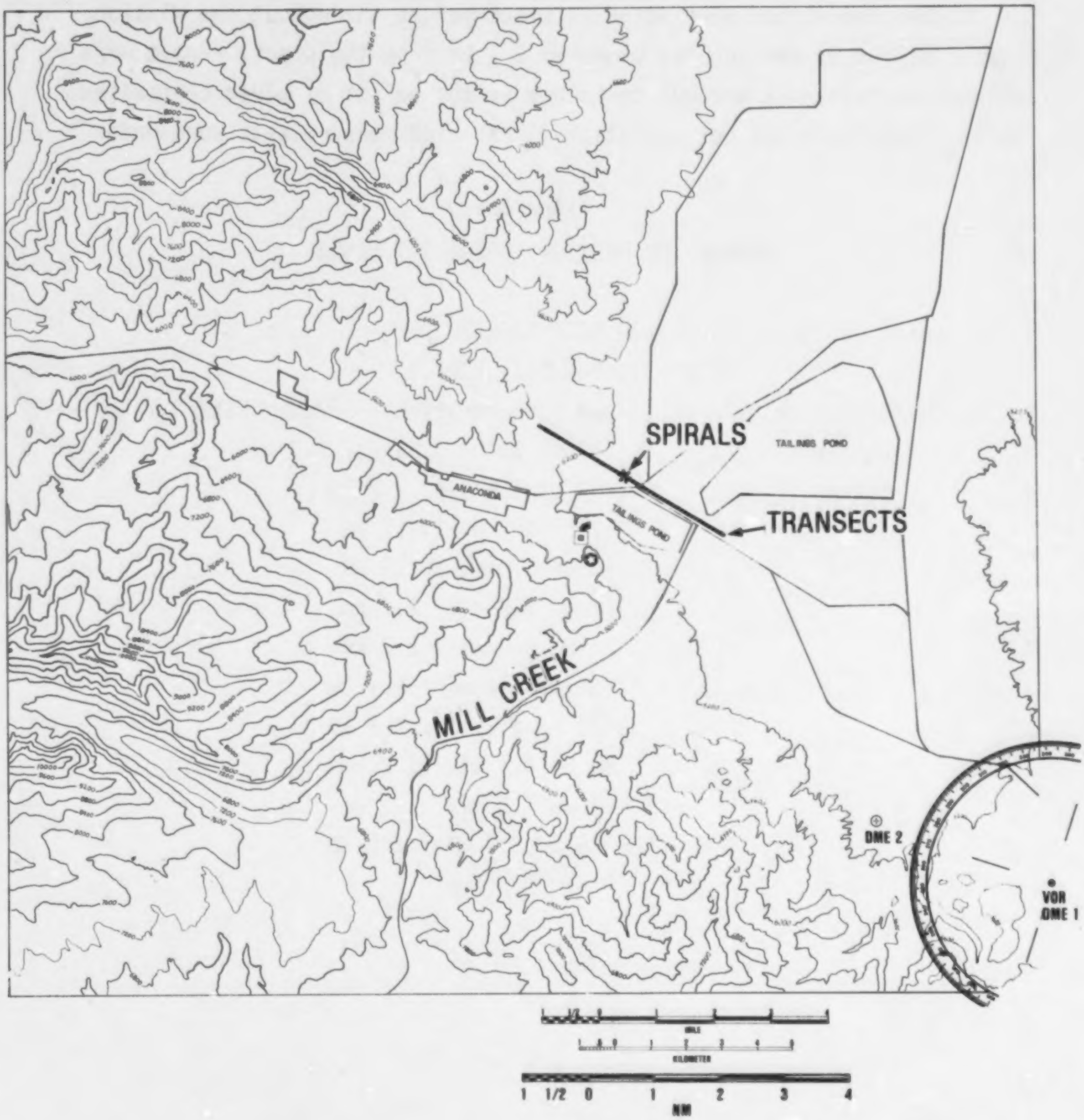

Figure A-1. Sampling Locations, October 1, 1976.

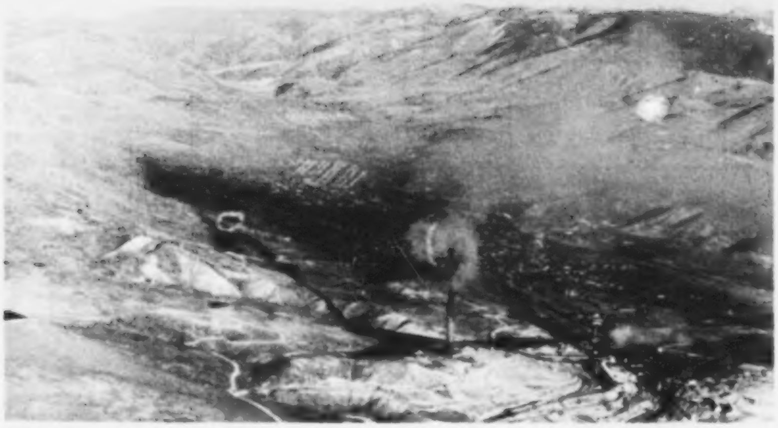

Figure A-2. Plume, October 1, 1976.

BEGINNING CLOCK TIME 072417
ENDING CLOCK TIME 073247

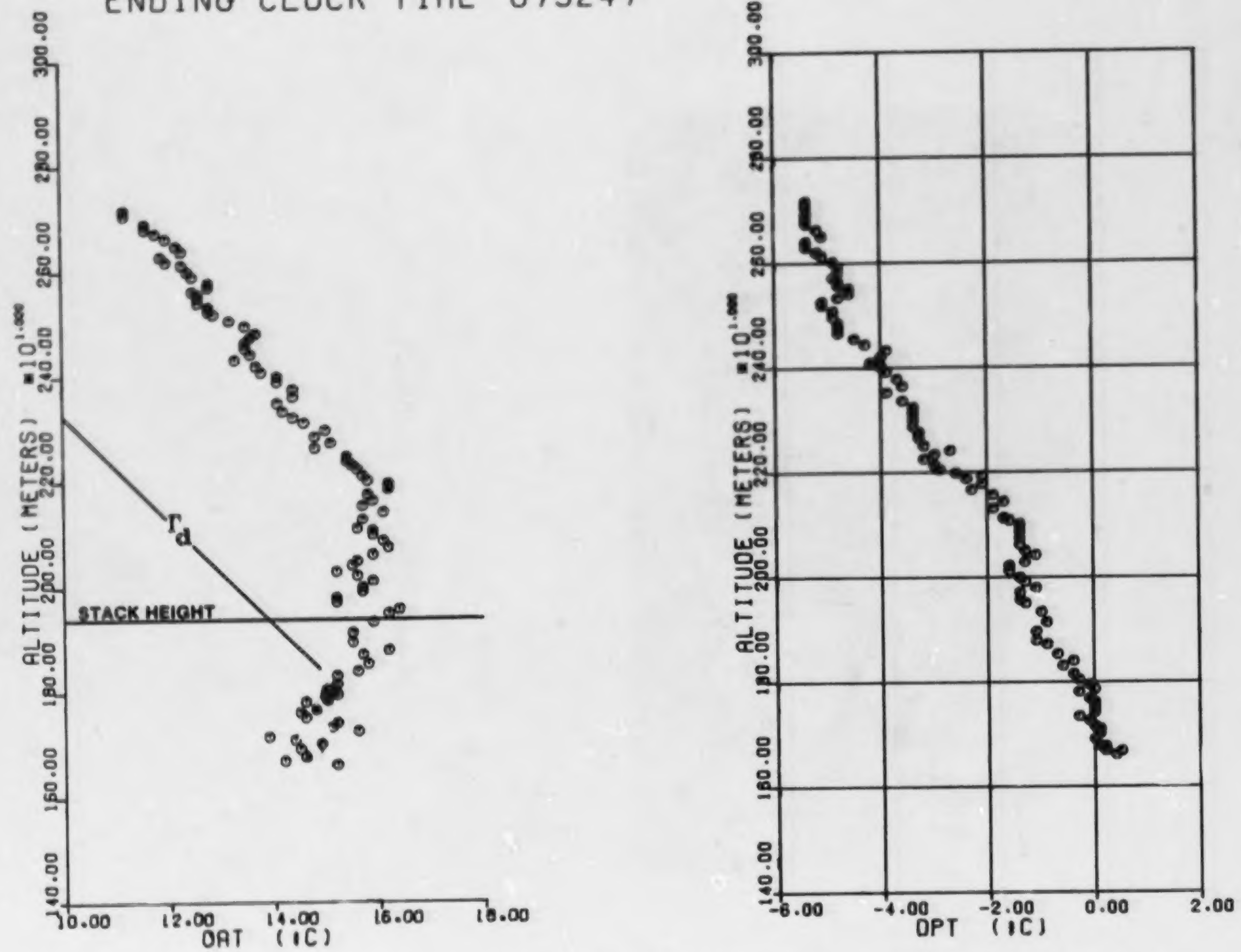

Figure A-3. Temperature and Dewpoint Soundings, 0724 MST, October 1, 1976.

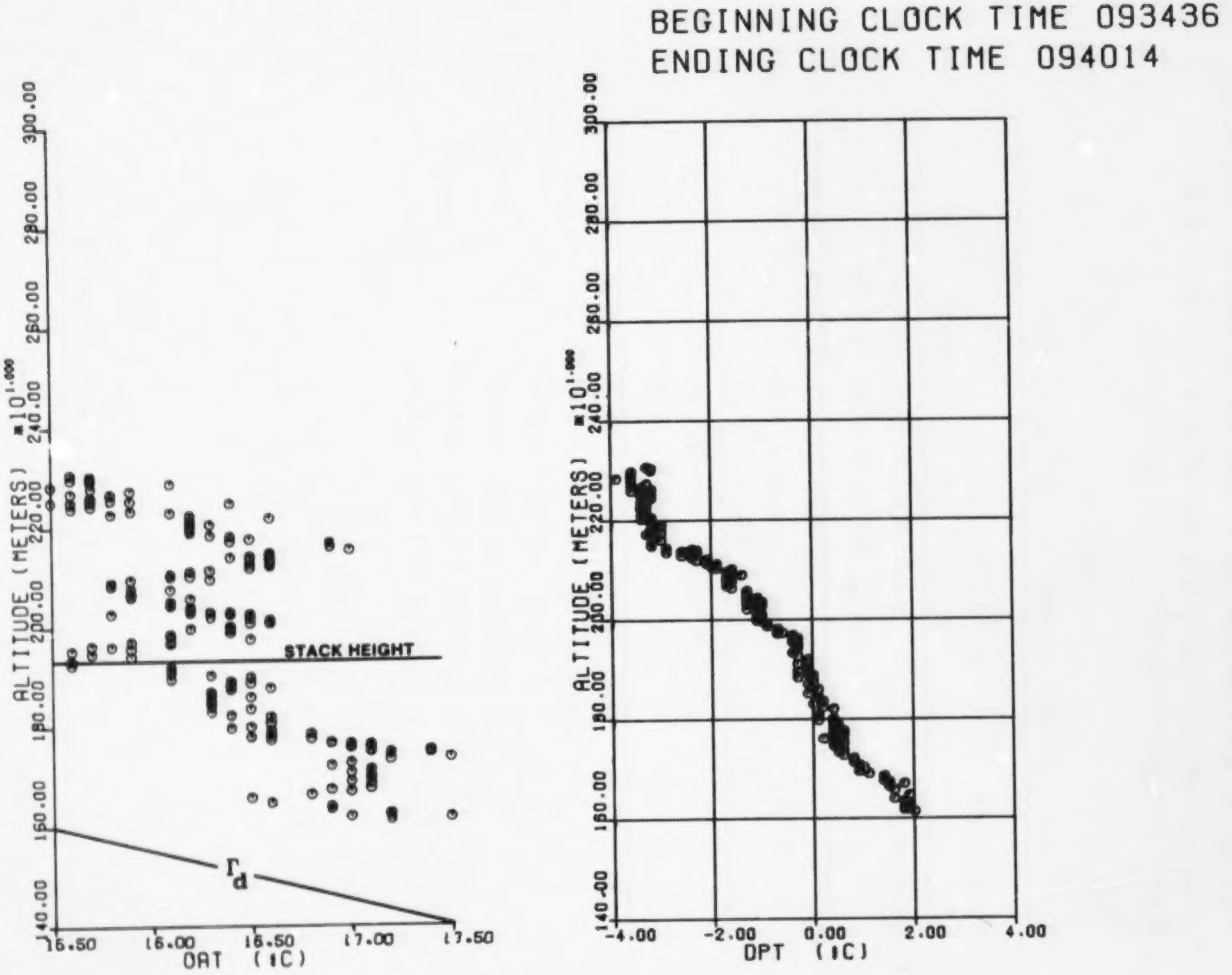

Figure A-4. Temperature and Dewpoint Soundings, 0934 MST, October 1, 1976.

October 4, 1976 0623-0827 MST

Neutral conditions were observed throughout the mission (Figures A-7 and A-8). Spirals and transects were performed at 2.5 and 5.8 km (Figure A-5). The SO_2 instrument was not operational.

TABLE A-2

SUMMARY OF MISSION, OCTOBER 4, 1976

1. Butte Weather: 0550 50 OVC 320/05
   0855 50 SCT 150 SCT 300/10
2. Three-minute σ_y, B_{scat}: 88 m/ 34 m/ 3 cases/ 2.5 km
   453 m/ 113 m/ 3 cases/ 5.8 km
3. Centerline Height/ Distance/ Concentration: ≈1911 m/ 2.5 km/ ---
4. σ_z, Spiral, B_{scat}: 168 m/ 6.0 min/ 2.5 km
   108 m/ 4.6 min/ 2.5 km
   151 m/ 5.0 min/ 2.5 km
   92 m/ 4.7 min/ 2.5 km
   89 m/ 3.0 min/ 2.5 km
   96 m/ 5.2 min/ 5.8 km
   51 m/ 3.0 min/ 5.8 km
   118 m/ 7.2 min/ 5.8 km
   60 m/ 4.1 min/ 5.8 km
   106 m/ 4.1 min/ 5.8 km

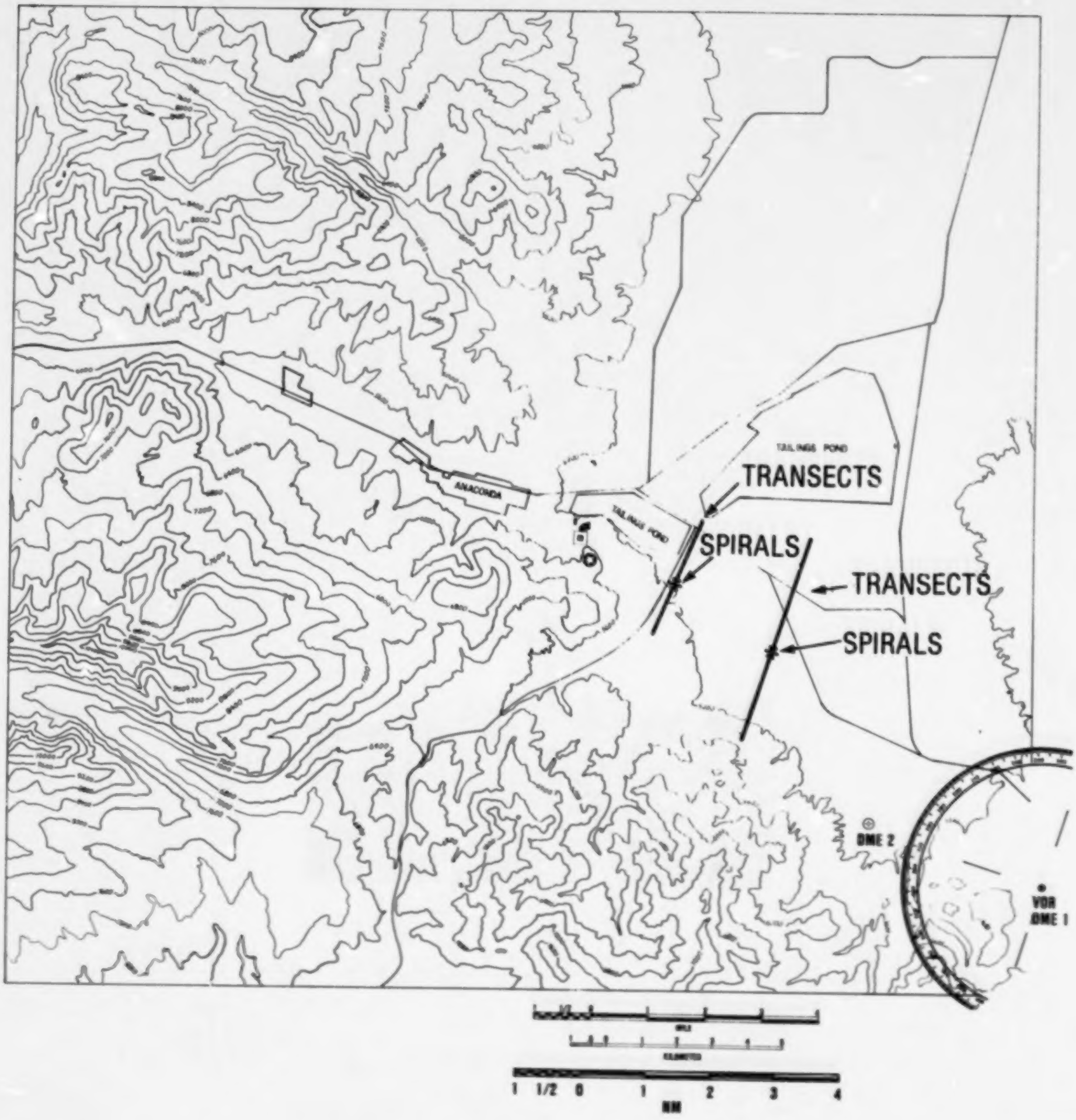

Figure A-5. Sampling Locations, October 4, 1976.

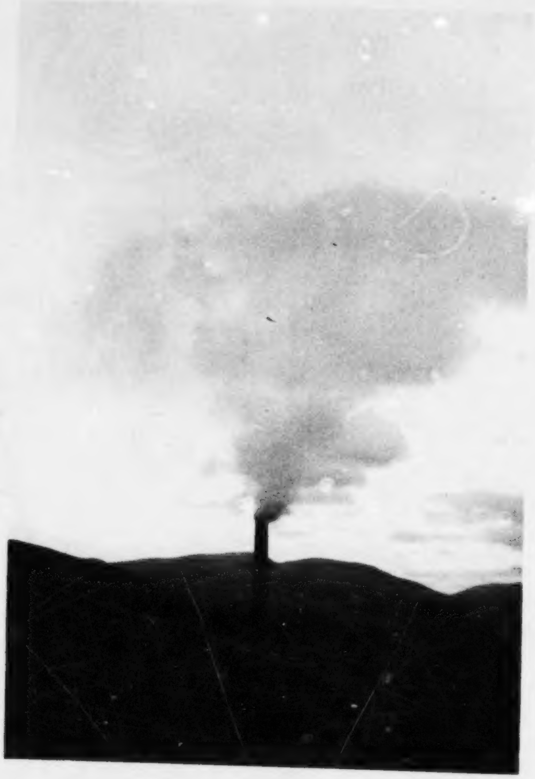

Figure A-6. Plume, October 4, 1976.

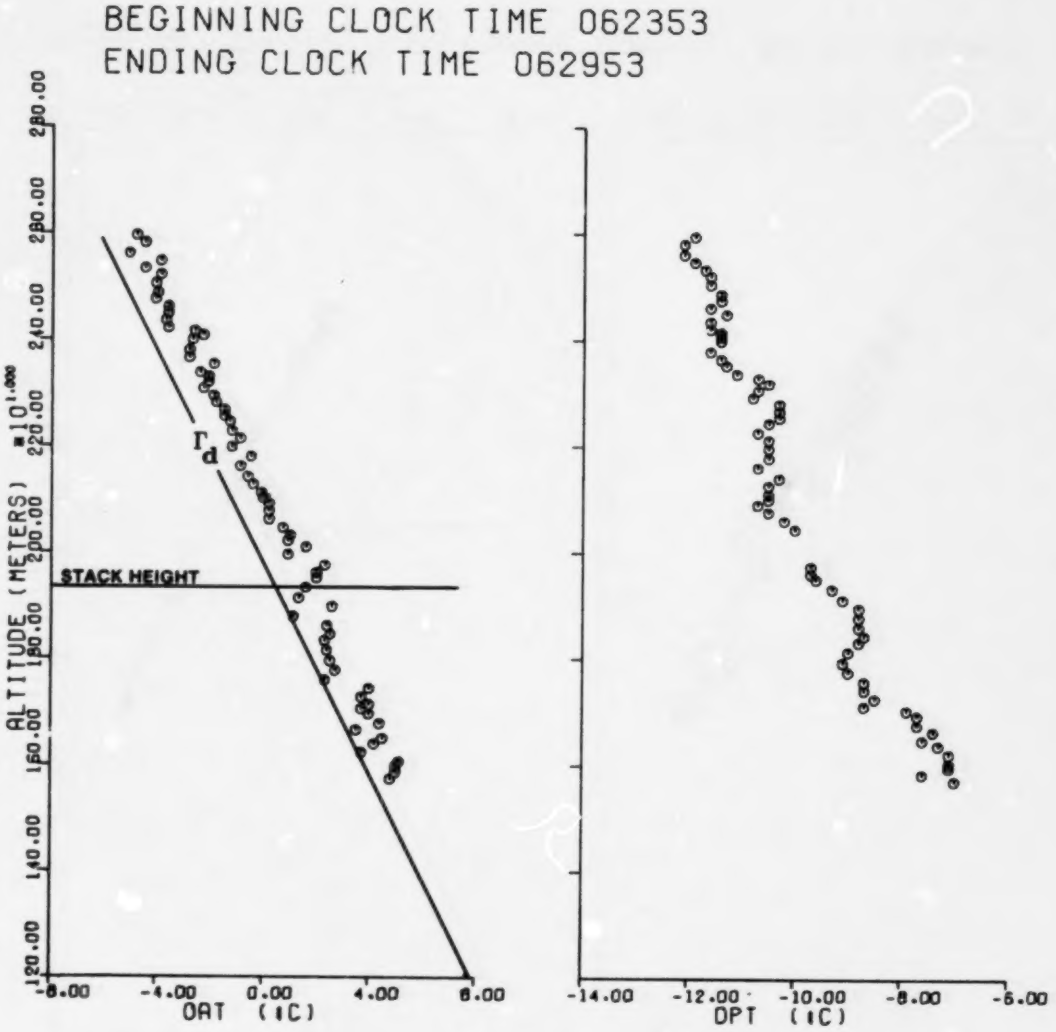

Figure A-7. Temperature and Dewpoint Soundings, 0623 MST, October 4, 1976.

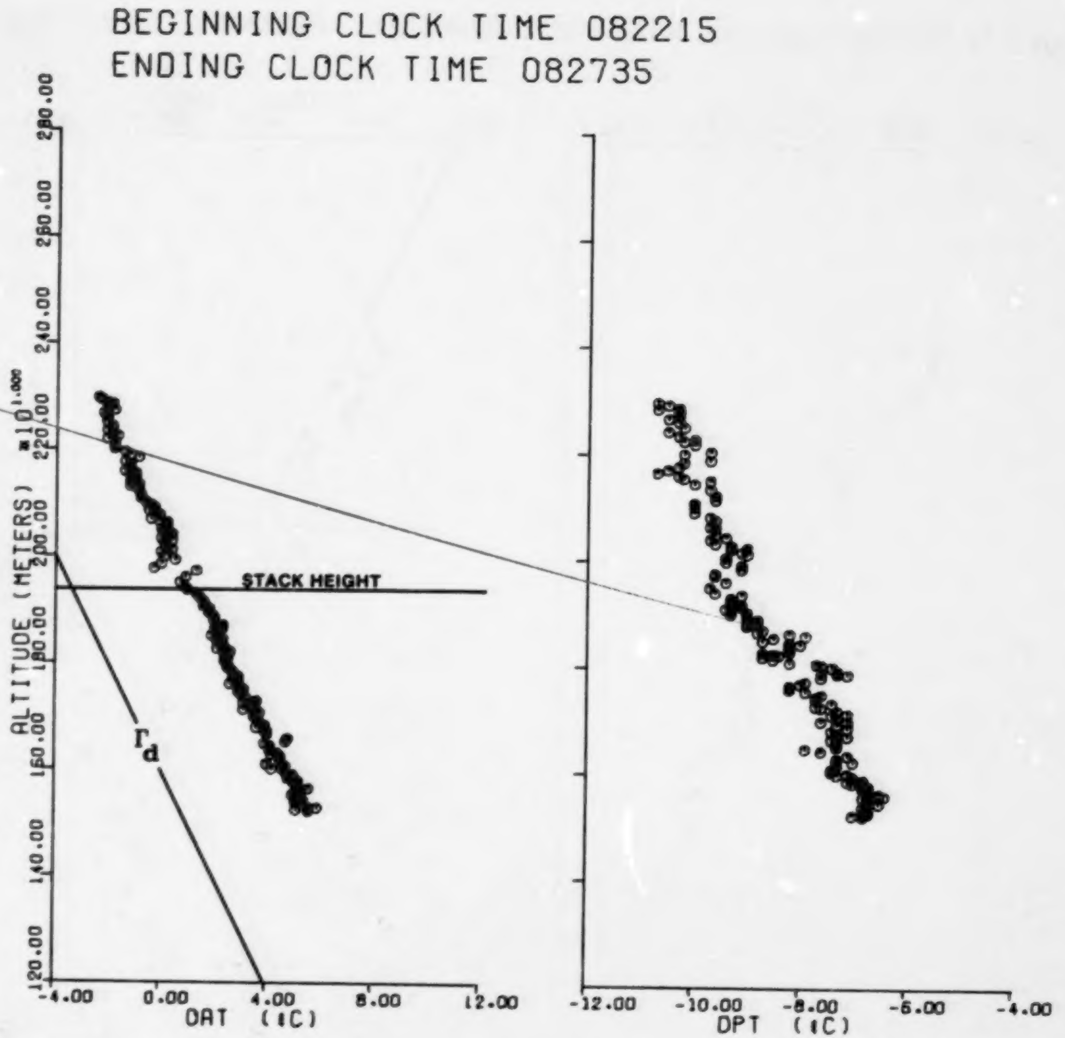

Figure A-8. Temperature and Dewpoint Soundings, 0822 MST, October 4, 1976.

October 5, 1976 0556-0823 MST

Stable conditions were observed throughout the sampling period. The SO_2 instrument was not operational. Spirals and transects were made through the plume at various altitudes 3.0 km from the stack.

TABLE A-3

SUMMARY OF MISSION, OCTOBER 5, 1976

1. Butte Weather: 0550 W1OX* 150/05
   0850 100 BRKN CLM
2. Plant Emissions, SO_2: 0600-0700 10.7 X 10^9 μg/s
   0700-0800 12.7 X 10^9 μg/s
   0800-0900 10.7 X 10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 2042 m/ 3.0 km/ --
4. Three-minute σ_y, B_{scat}: 290 m/ 90 m/ 7 cases/ 3.0 km
5. σ_z, Spiral, B_{scat}: 107 m/ 3.0 min/ 3.0 km
   81 m/ 1.5 min/ 3.0 km
6. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (^{o})	Speed (m/s)
0758	1950	244	3
	2040	246	3
0829	1950	229	5
	2040	229	5

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* Indefinite, 1000 ft. obscured.

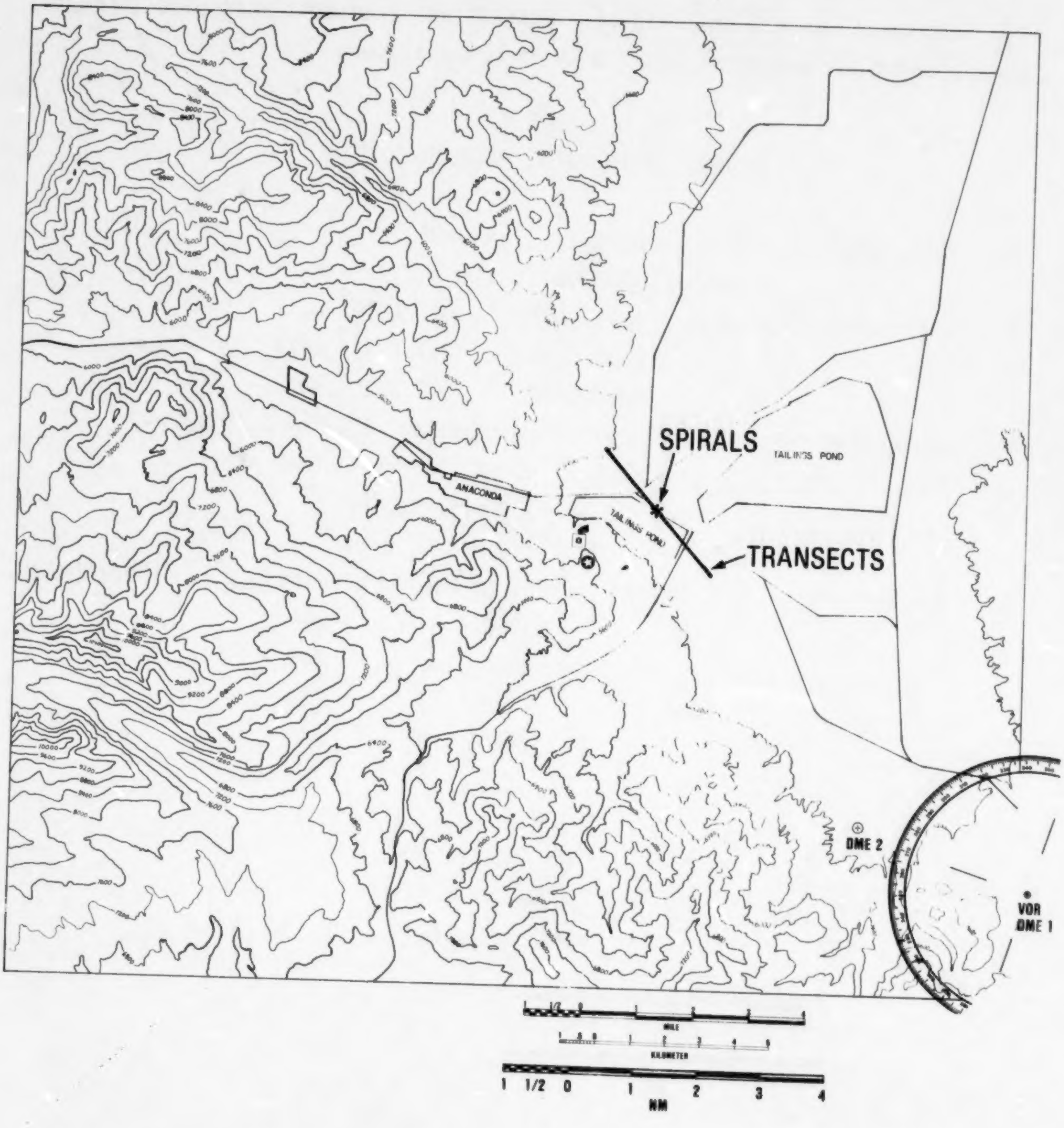

Figure A-9. Sampling Locations, October 5, 1976.

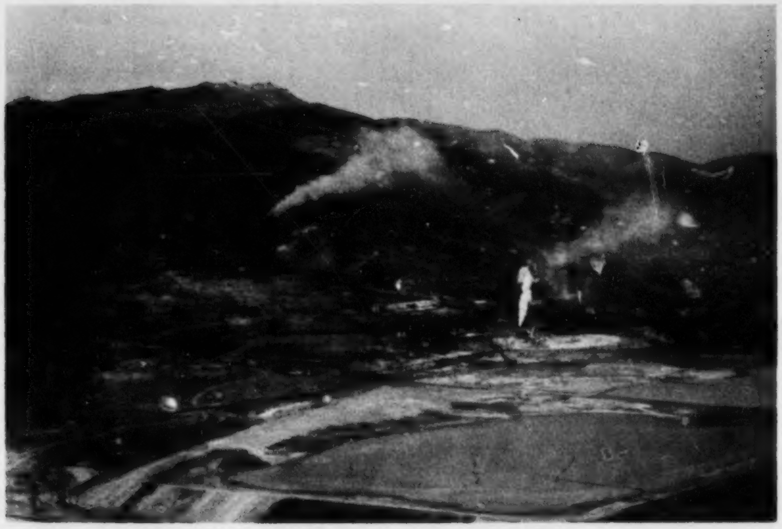

Figure A-10. Plume, October 5, 1976.

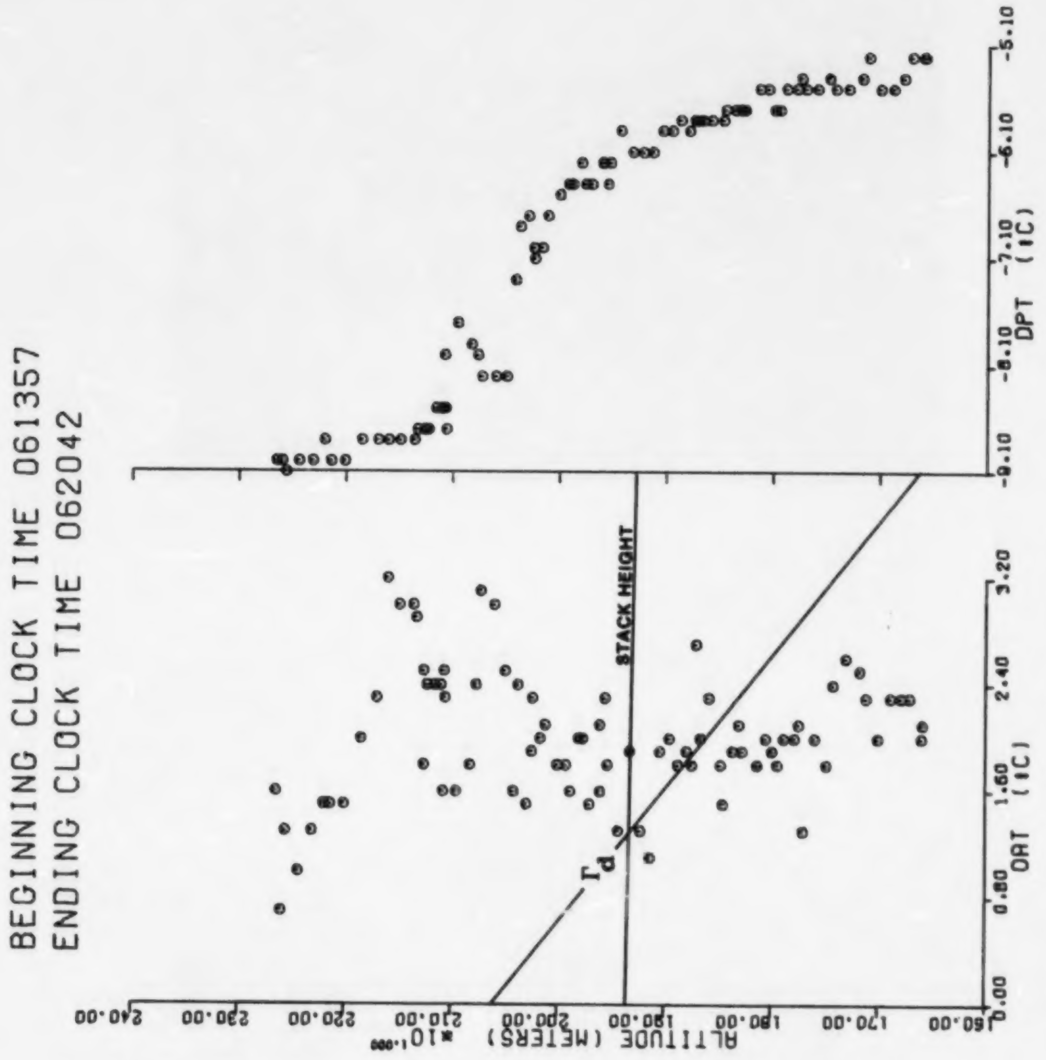

Figure A-11. Temperature and Dewpoint Soundings, 0613 MST, October 5, 1976.

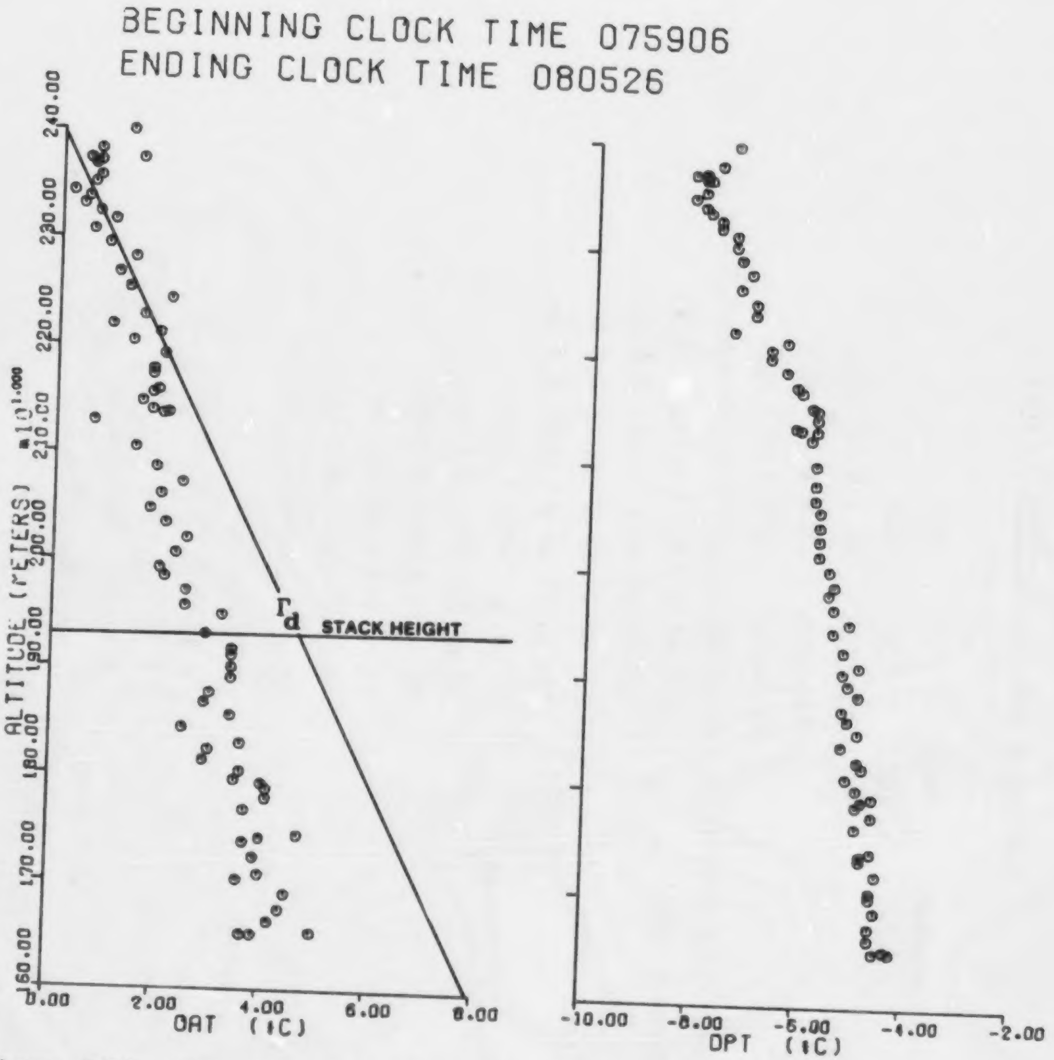

Figure A-12. Temperature and Dewpoint Soundings, 0759 MST, October 5, 1976.

October 7, 1976 0619-0826 MST

Clear skies, light winds and stable conditions were noted throughout the sampling period (Figures A-15 and A-16). Multiple spirals followed by traverses at the height of the plume centerline were made at 1.5 and 4.4 km east-southeast of the stack (Figure A-13).

TABLE A-4
SUMMARY OF MISSION, OCTOBER 7, 1976

1. Butte Weather: 0654 CLR CLM
   0955 CLR CLM
2. Plant Emissions, SO_2: 0600-0700 10.2×10^9 μg/s
   0700-0800 9.4×10^9 μg/s
   0800-0900 12.4×10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 2250 m/ 1.5 km/ 20.5 ppm
4. Three-minute σ_y, SO_2: 359 m/ 112 m/ 3 cases/ 1.5 km
   575 m/ 91 m/ 6 cases/ 4.4 km
   Three-minute σ_y, B_{scat}: 299 m/ 47 m/ 3 cases/ 1.5 km
   556 m/ 74 m/ 6 cases/ 4.4 km
5. σ_z, Spiral, SO_2: 59 m/ 3.5 min/ 1.5 km
   38 m/ 3.5 min/ 1.5 km
   40 m/ 3.0 min/ 1.5 km
   65 m/ 4.3 min/ 4.4 km
   60 m/ 4.0 min/ 4.4 km
   61 m/ 1.2 min/ 4.4 km
6. σ_z, Spiral, B_{scat}: 45 m/ 1.3 min/ 1.5 km
   66 m/ 3.5 min/ 1.5 km
   41 m/ 3.5 min/ 1.5 km
   70 m/ 3.3 min/ 4.4 km
   68 m/ 2.6 min/ 4.4 km
   61 m/ 1.3 min/ 4.4 km
   55 m/ 0.9 min/ 4.4 km
   63 m/ 4.0 min/ 4.4 km

7. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0725	1950	046	5
	2250	307	6
0755	1950	051	3
0825	1950	023	6
	2250	020	7
0855	1950	055	4
	2250	315	1

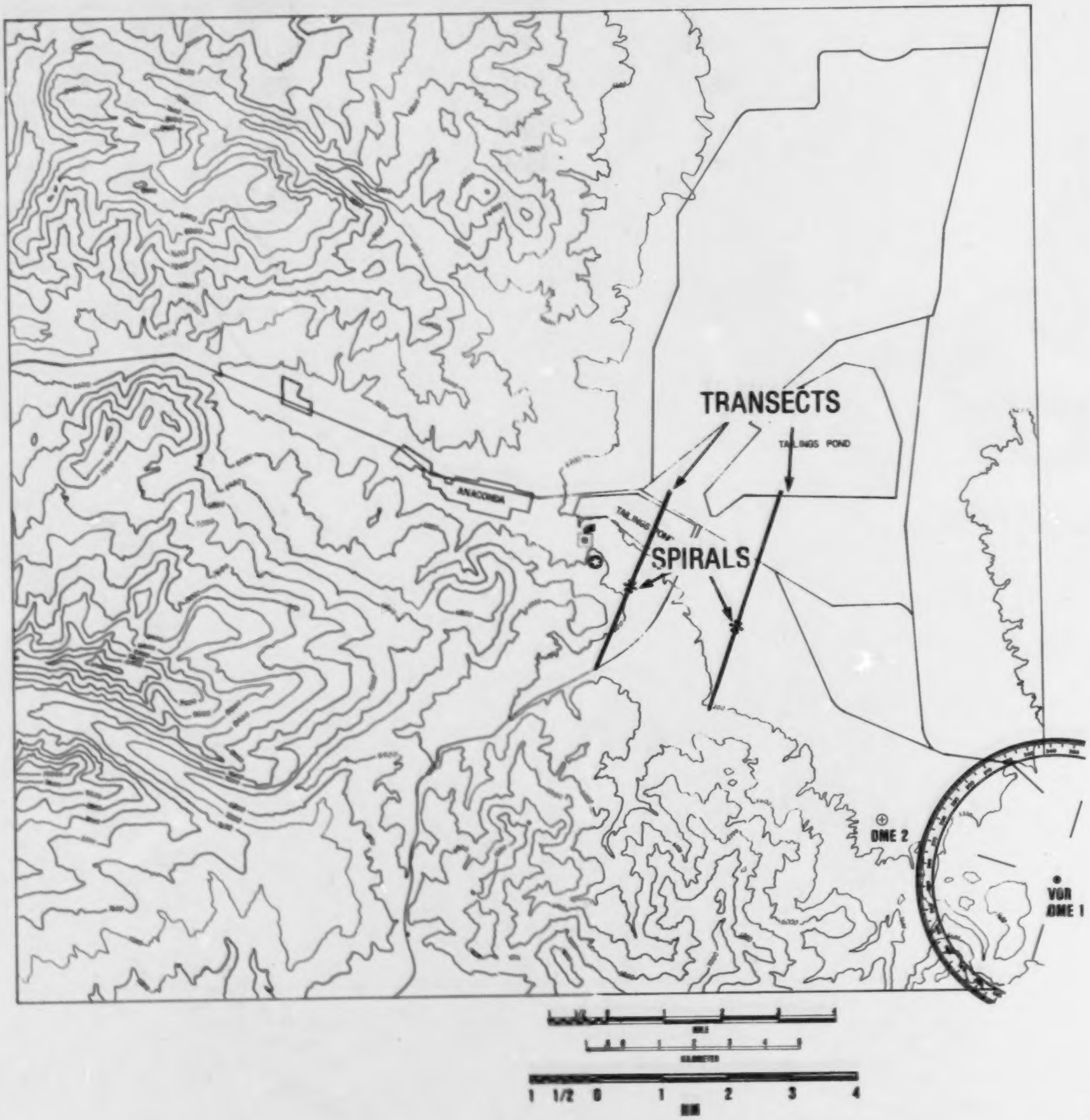

Figure A-13. Sampling Locations, October 7, 1976.

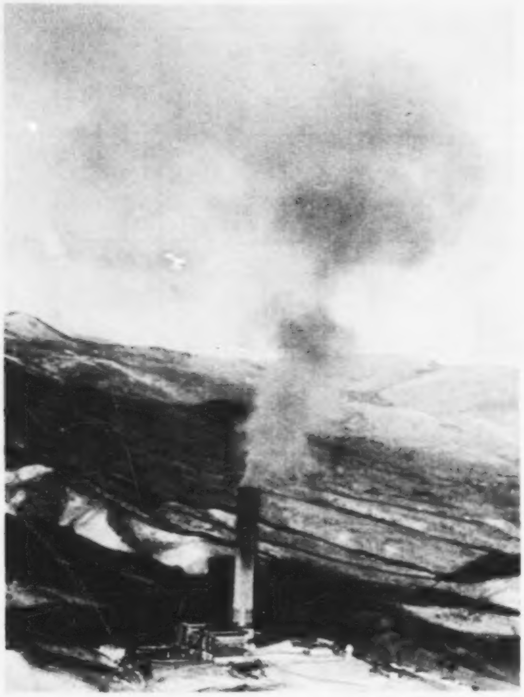

Figure A-14. Plume, October 7, 1976.

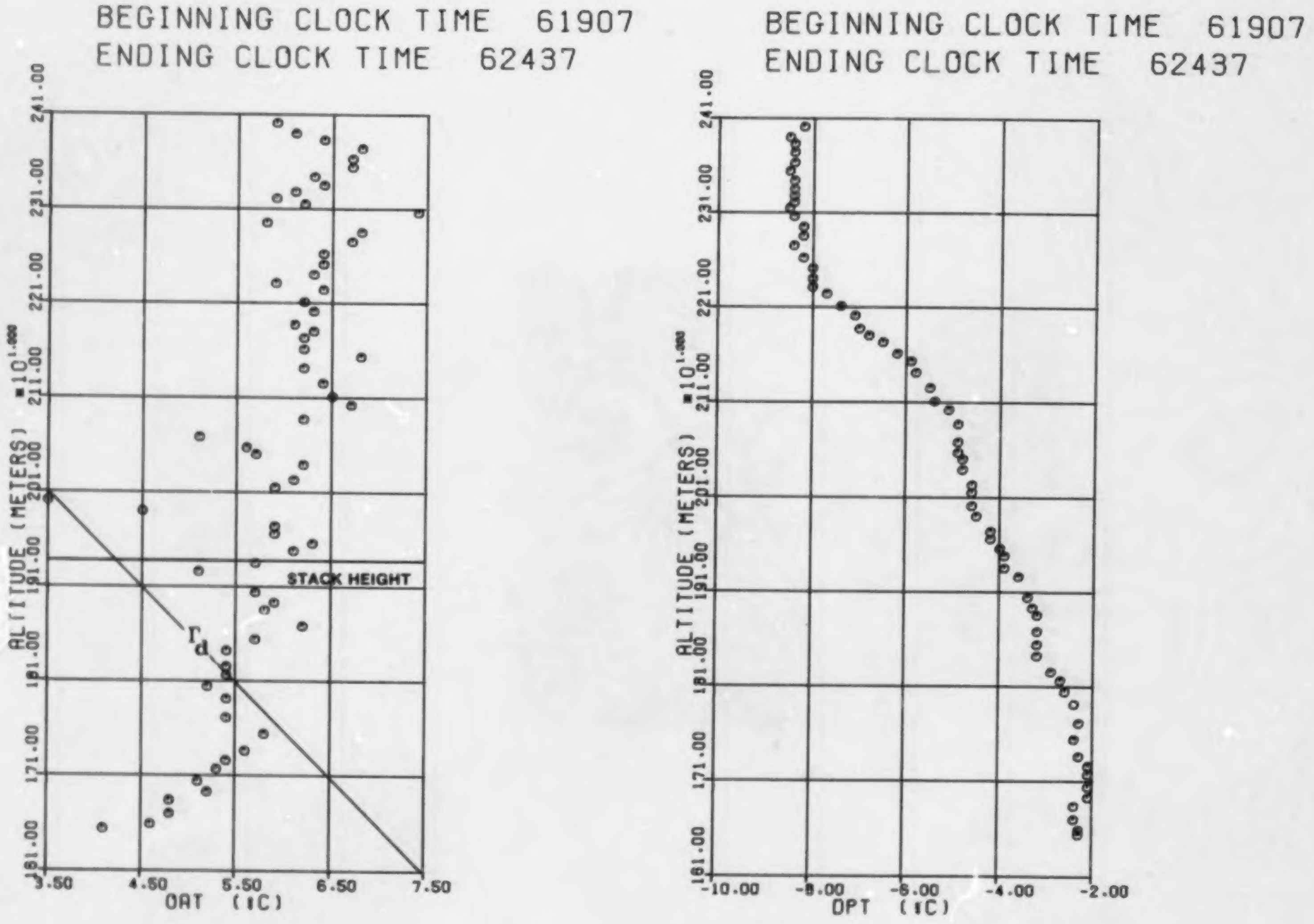

Figure A-15. Temperature and Dewpoint Soundings, 0619 MST, October 7, 1976.

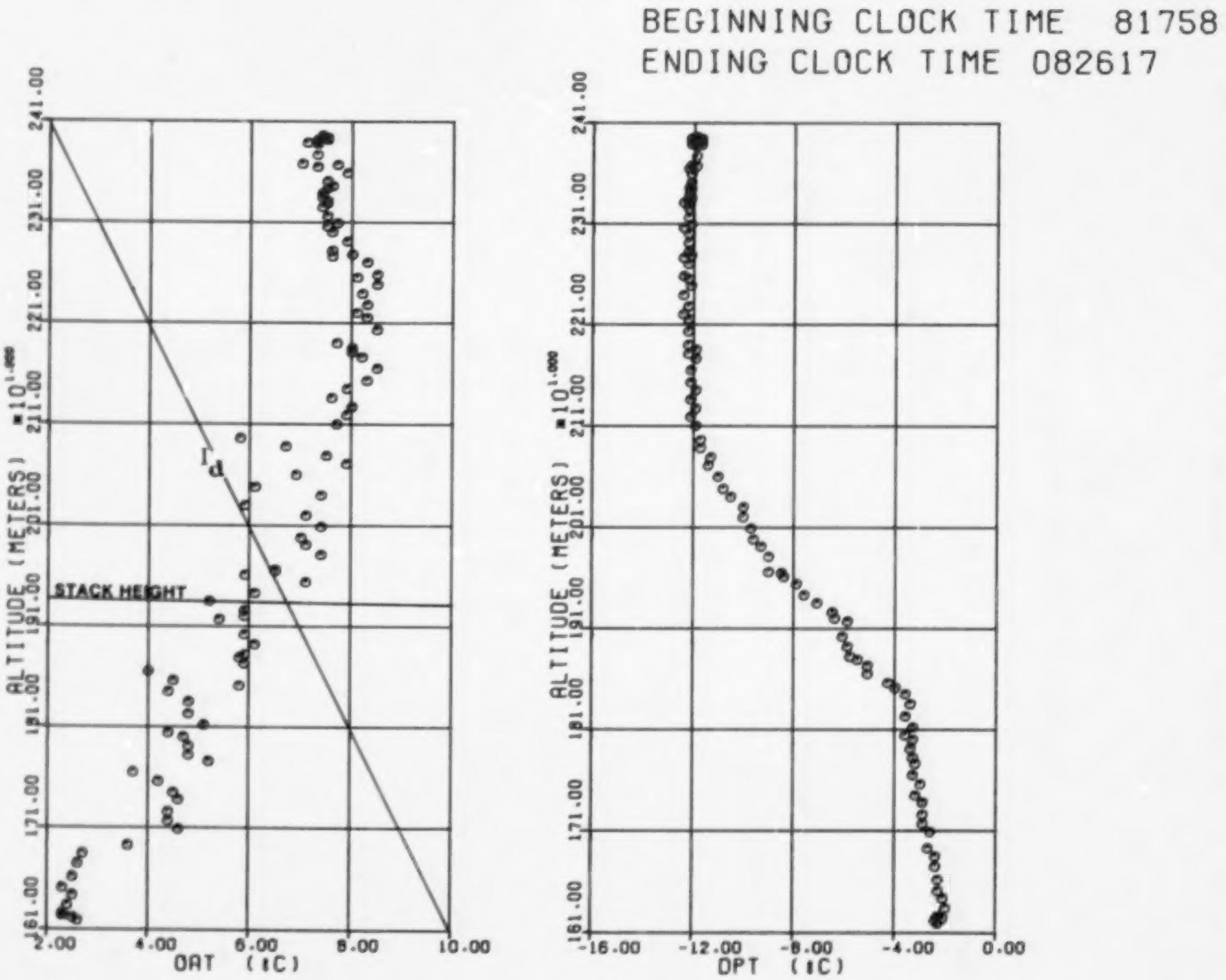

Figure A-16. Temperature and Dewpoint Soundings, 0826 MST, October 7, 1976.

October 8, 1976 0624-0856 MST

Clear skies and stable conditions were observed during the mission. Multiple spirals and transects were made at 1.5 and 3.7 km east of the stack.

TABLE A-5
SUMMARY OF MISSION, OCTOBER 8, 1976

1.	Butte Weather:	0556	CLR	CLM
		0850	CLR	080/04
2.	Plant Emissions, SO_2:	0600-0700	12.2×10^9 μg/s	
		0700-0800	5.8×10^9 μg/s	
3.	Centerline Height/ Distance/ Concentration:	≈2200 m/ 1.5 km/ 3.3 ppm		
4.	Three-minute σ_y, SO_2:	471 m/ 126 m/ 3 cases/ 1.5 km		
		346 m/ 67 m/ 4 cases/ 3.7 km		
	Three-minute σ_y, B_{scat}:	503 m/ 100 m/ 3 cases/ 1.5 km		
		259 m/ 71 m/ 2 cases/ 3.7 km		
5.	σ_z, Spiral, SO_2:	43 m/ 3.8 min/ 1.5 km		
		63 m/ 5.5 min/ 1.5 km		
		49 m/ 3.0 min/ 1.5 km		
		83 m/ 3.6 min/ 1.5 km		
		122 m/ 4.3 min/ 1.5 km		
		97 m/ 4.5 min/ 1.5 km		
		102 m/ 5.0 min/ 3.7 km		
		72 m/ 4.5 min/ 3.7 km		
		75 m/ 2.7 min/ 3.7 km		
		55 m/ 3.4 min/ 3.7 km		
6.	σ_z, Spiral, B_{scat}:	55 m/ 4.0 min/ 1.5 km		
		73 m/ 5.0 min/ 1.5 km		
		78 m/ 4.0 min/ 1.5 km		
		55 m/ 2.0 min/ 1.5 km		
		57 m/ 2.7 min/ 3.7 km		
		52 m/ 3.4 min/ 3.7 km		

7. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (^{o})	Speed (m/s)
0725	1950	228	7
	2010	232	6
0755	1950	229	9
	2010	226	8
0825	1950	224	9
	2010	225	9
0855	1950	229	8
	2010	234	6

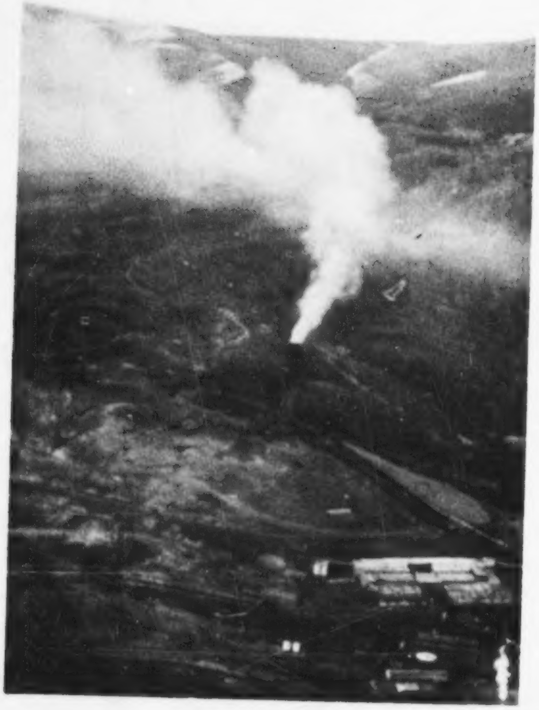

Figure A-17. Plume, October 8, 1976.

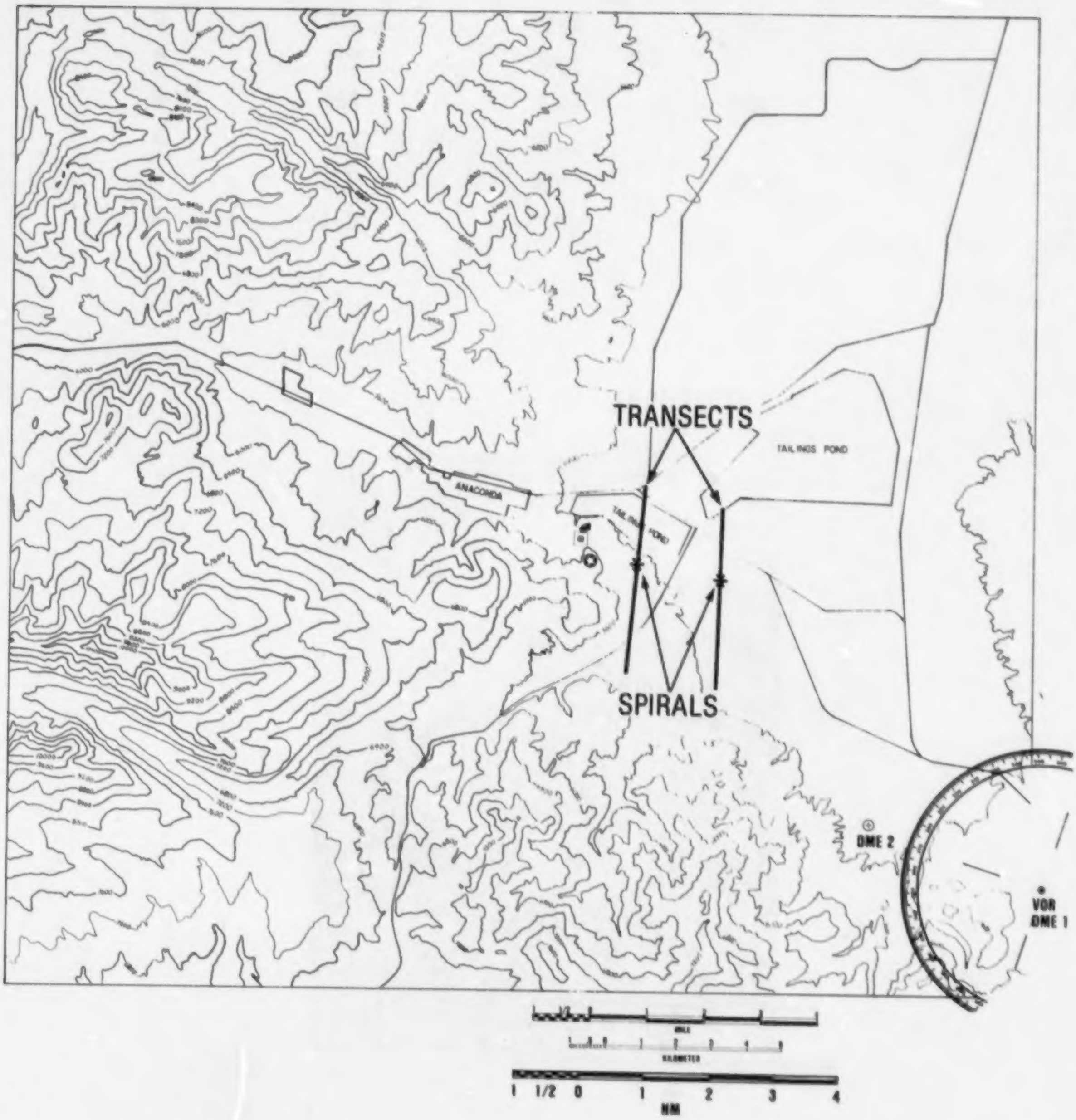

Figure A-18. Sampling Locations, October 8, 1976.

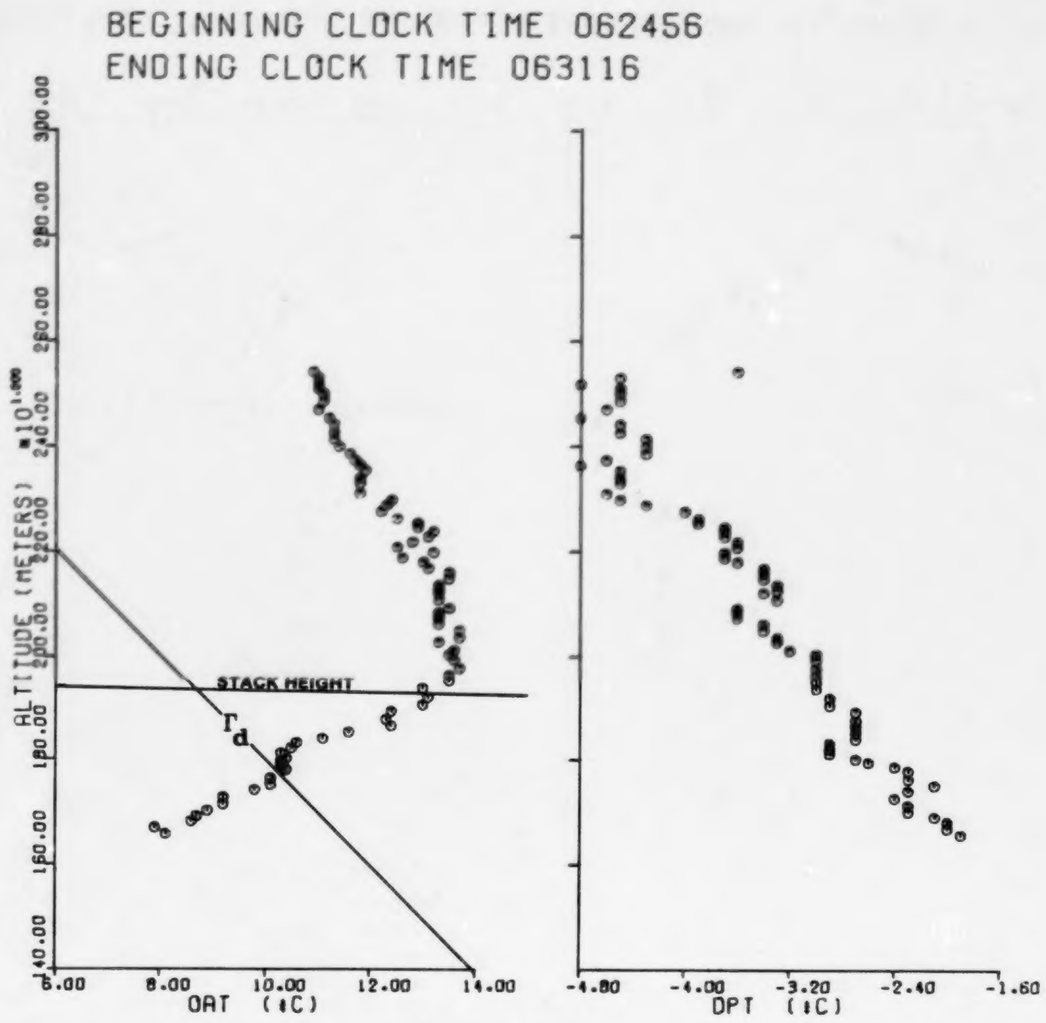

Figure A-19. Temperature and Dewpoint Soundings, 0624 MST, October 8, 1976.

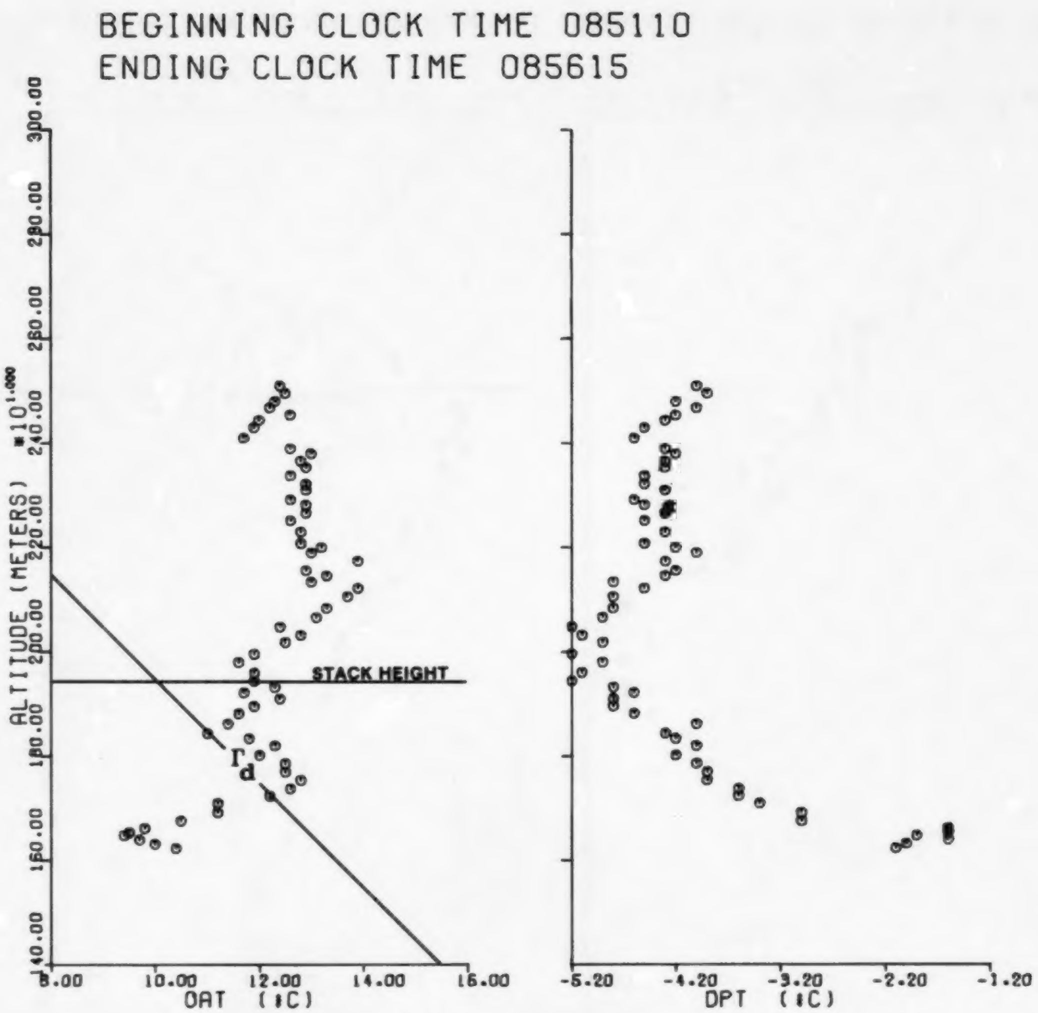

Figure A-20. Temperature and Dewpoint Soundings, 0851 MST, October 8, 1976.

October 12, 1976 0645-0839 MST

Stable conditions were replaced by neutral conditions during the mission. Transects were made at various altitudes 2.7 km northeast of the stack (Figure A-21).

TABLE A-6
SUMMARY OF MISSION, OCTOBER 12, 1976

1. Butte Weather: 0550 CLR 150/03
   0950 200 BRKN 360/04
2. Plant Emissions, SO_2: Not available.
3. Centerline Height/ Distance/ Concentration: 1859 m/ 2.7 km/ 3.9 ppm
4. Three-minute σ_y, SO_2: 511 m/ 206 m/ 5 cases/ 2.7 km
   Three-minute σ_y, B_{scat}: 532 m/ 217 m/ 5 cases 2.7 km
5. σ_z, Spiral, SO_2: 85 m/ 2.1 min/ 2.7 km
   99 m/ 5.0 min/ 2.7 km
   120 m/ 8.5 min/ 2.7 km
6. σ_z, Spiral, B_{scat}: 48 m/ 0.7 min/ 2.7 km
7. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0730	1860	243	4
	1950	256	3
0800	1860	251	4
	1950	256	3
0900	1860	225	8
	1950	228	6

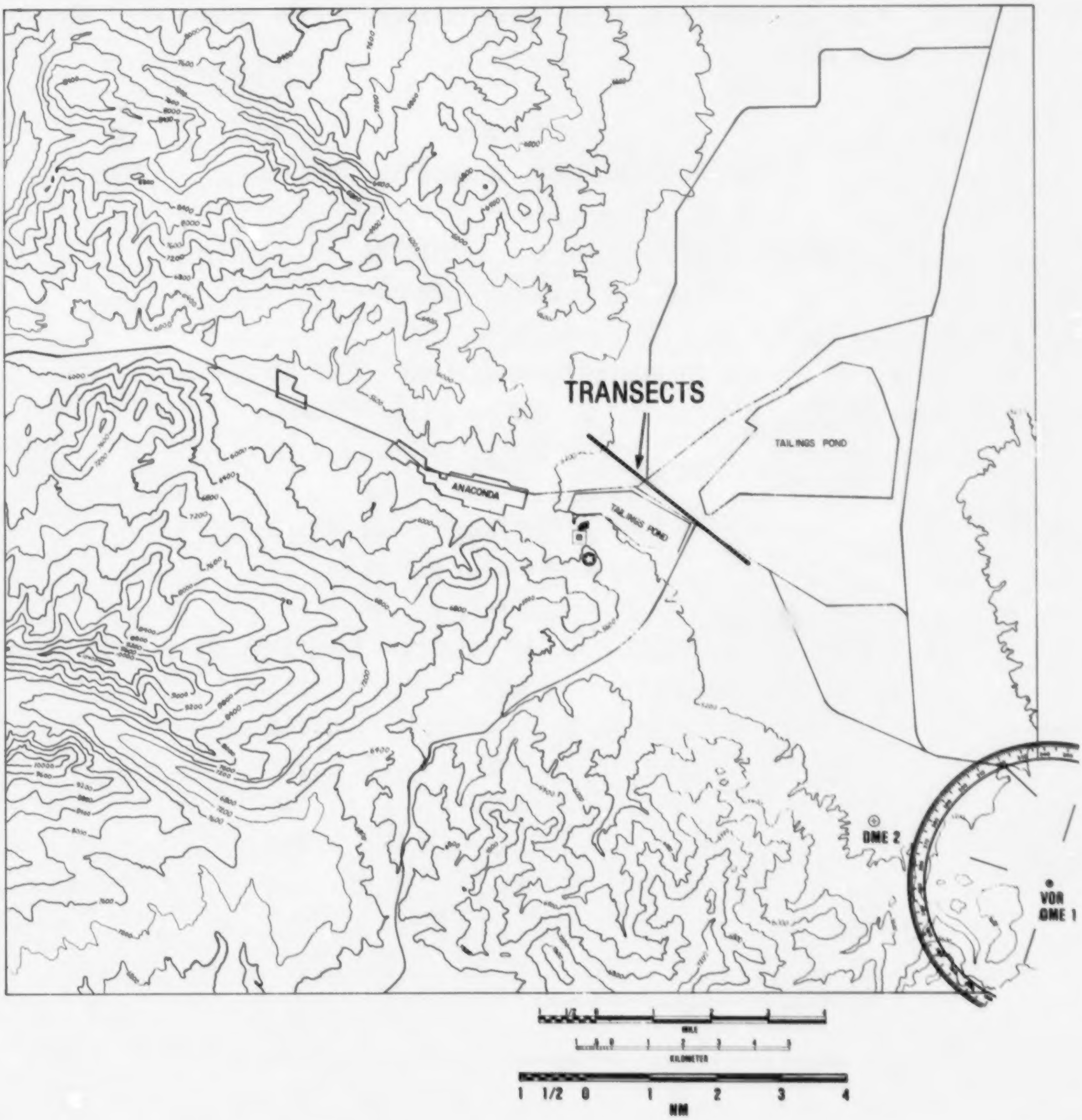

Figure A-21. Sampling Locations, October 12, 1976.

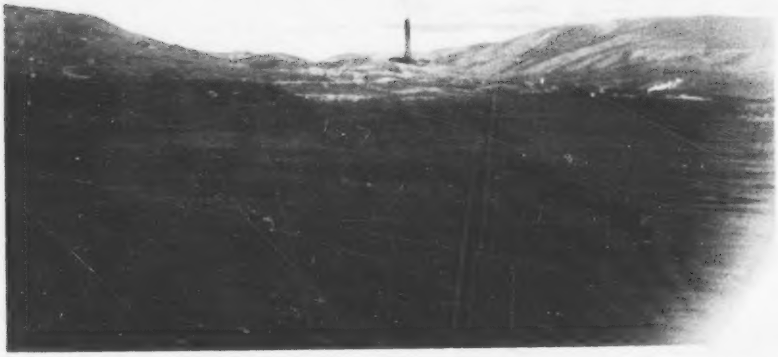

Figure A-22. Plume, October 12, 1976.

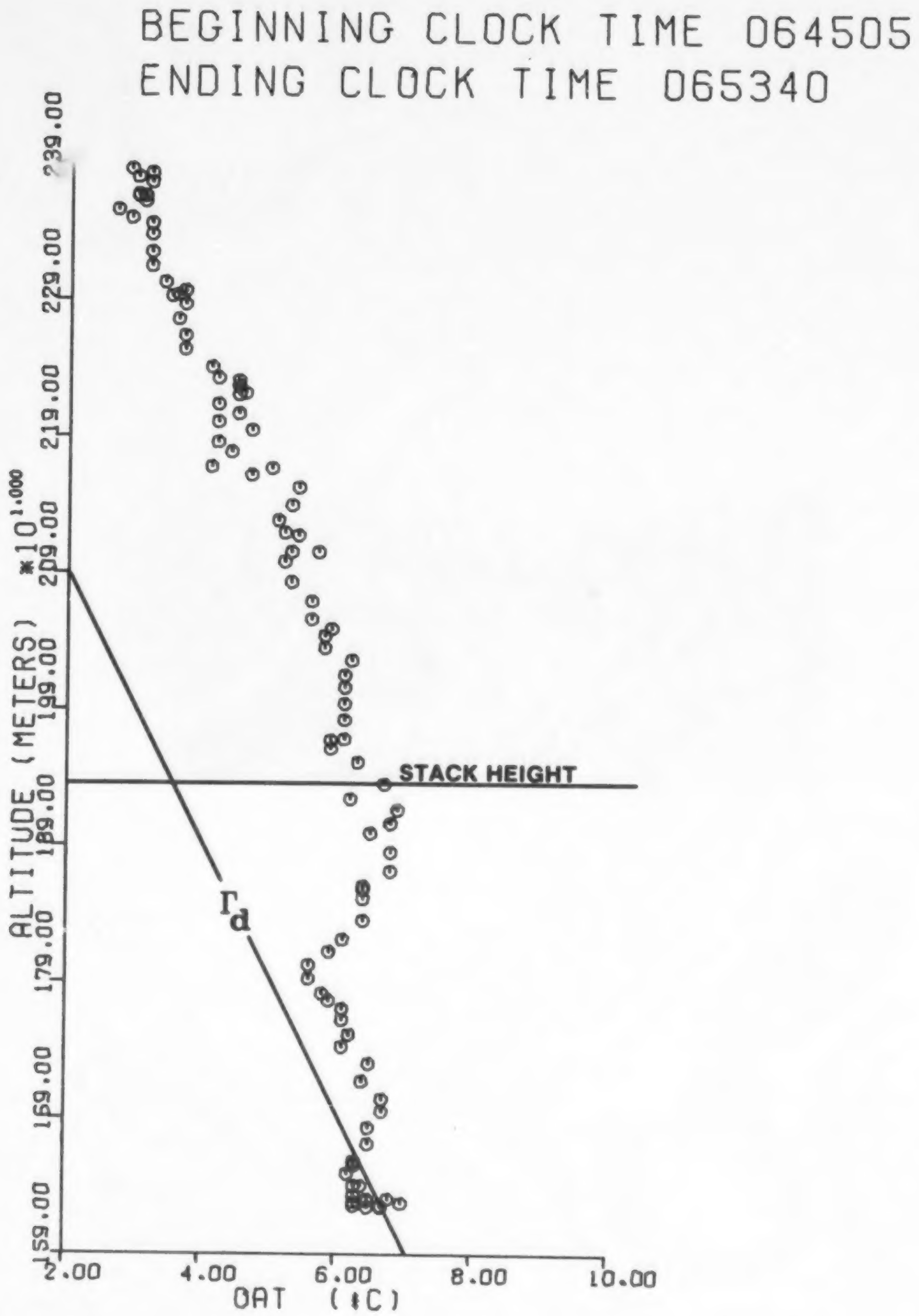

Figure A-23. Temperature Sounding, 0645 MST, October 12, 1976.

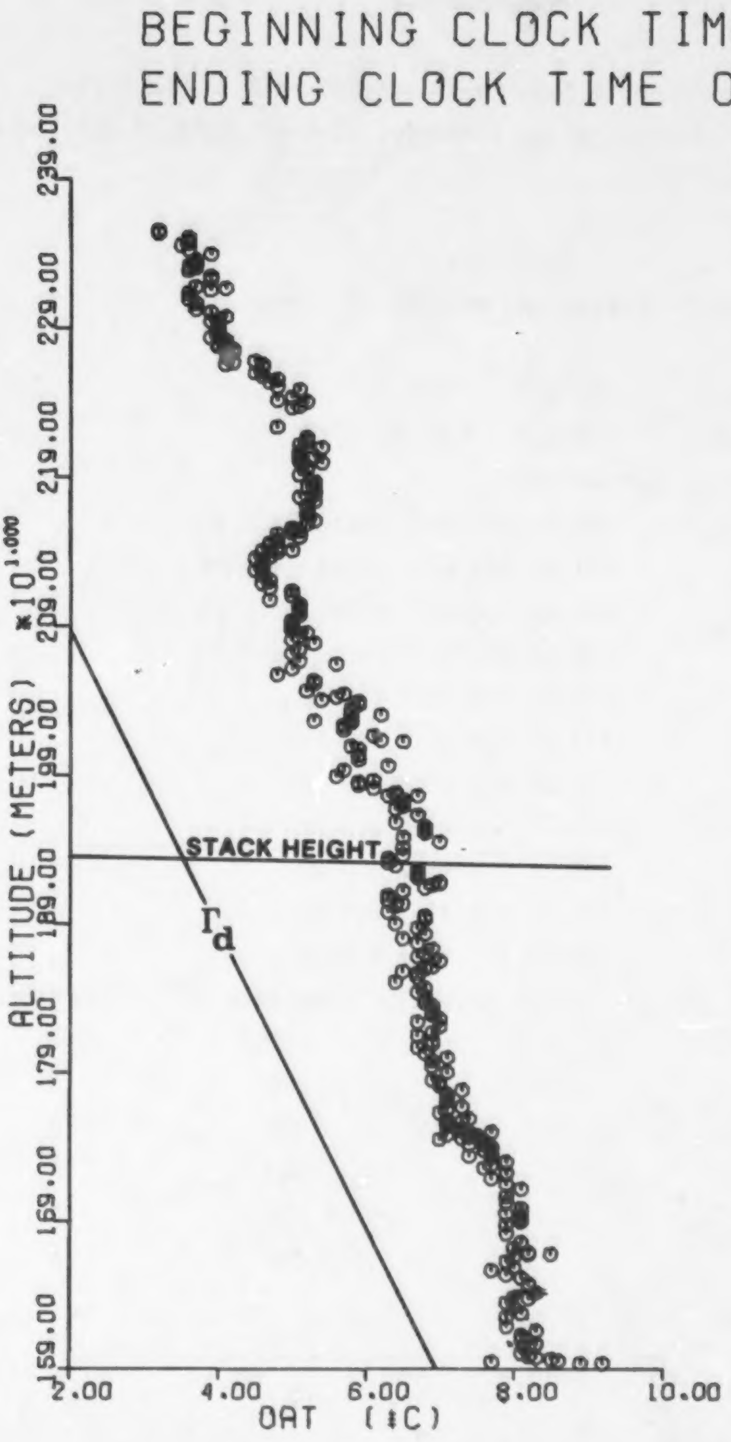

Figure A-24. Temperature Sounding, 0834 MST, October 12, 1976.

October 13, 1976 0638-0835 MST

Stable conditions produced a fanning plume (Figure A-27 and A-28). Multiple spirals, each followed by two traverses at the height of the centerline were made at 2.3 and 6.6 km.

TABLE A-7

SUMMARY OF MISSION, OCTOBER 13, 1976

1. Butte Weather: 0551 150 SCT 160/04
   0850 150 SCT 200 OVC 060/03
2. Plant Emissions, SO_2: Not available.
3. Three-minute σ_y, SO_2: 489 m/ 139 m/ 5 cases/ 2.3 km
   651 m/ 119 m/ 4 cases/ 6.6 km
   Three-minute σ_y, B_{scat}: 510 m/ 116 m/ 6 cases/ 2.3 km
   645 m/ 258 m/ 4 cases/ 6.6 km
4. σ_z, Spiral, SO_2: 150 m/ 5.5 min/ 2.3 km
5. σ_z, Spiral, B_{scat}: 143 m/ 3.8 min/ 2.3 km
   110 m/ 5.0 min/ 2.3 km
   140 m/ 3.9 min/ 2.3 km
   115 m/ 2.5 min/ 2.3 km
   125 m/ 3.2 min/ 6.6 km
   115 m/ 3.2 min/ 6.6 km
6. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (^{o})	Speed (m/s)
0730	1950	250	4
	2100	260	5
0800	1950	230	3
	2100	287	1
0830	1950	269	2
	2100	305	2

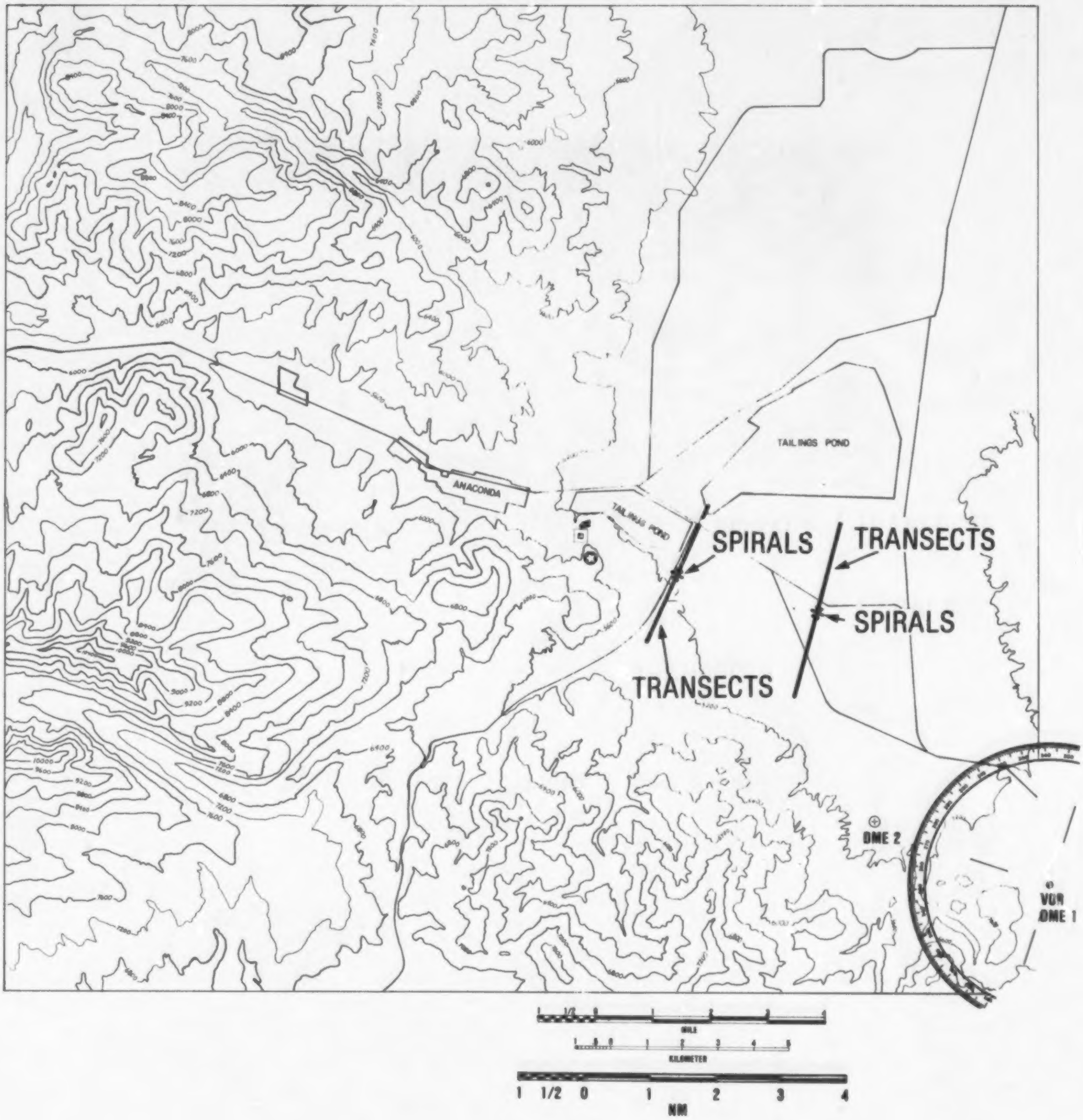

Figure A-25. Sampling Locations, October 13, 1976.

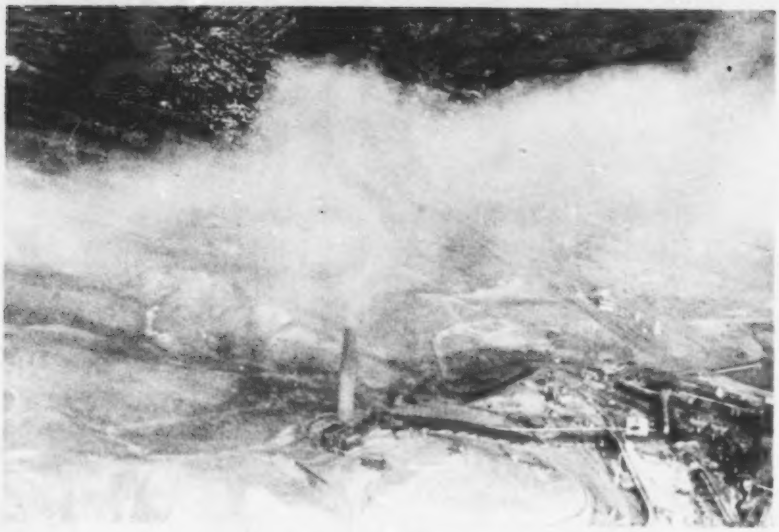

Figure A-26. Plume, October 13, 1976.

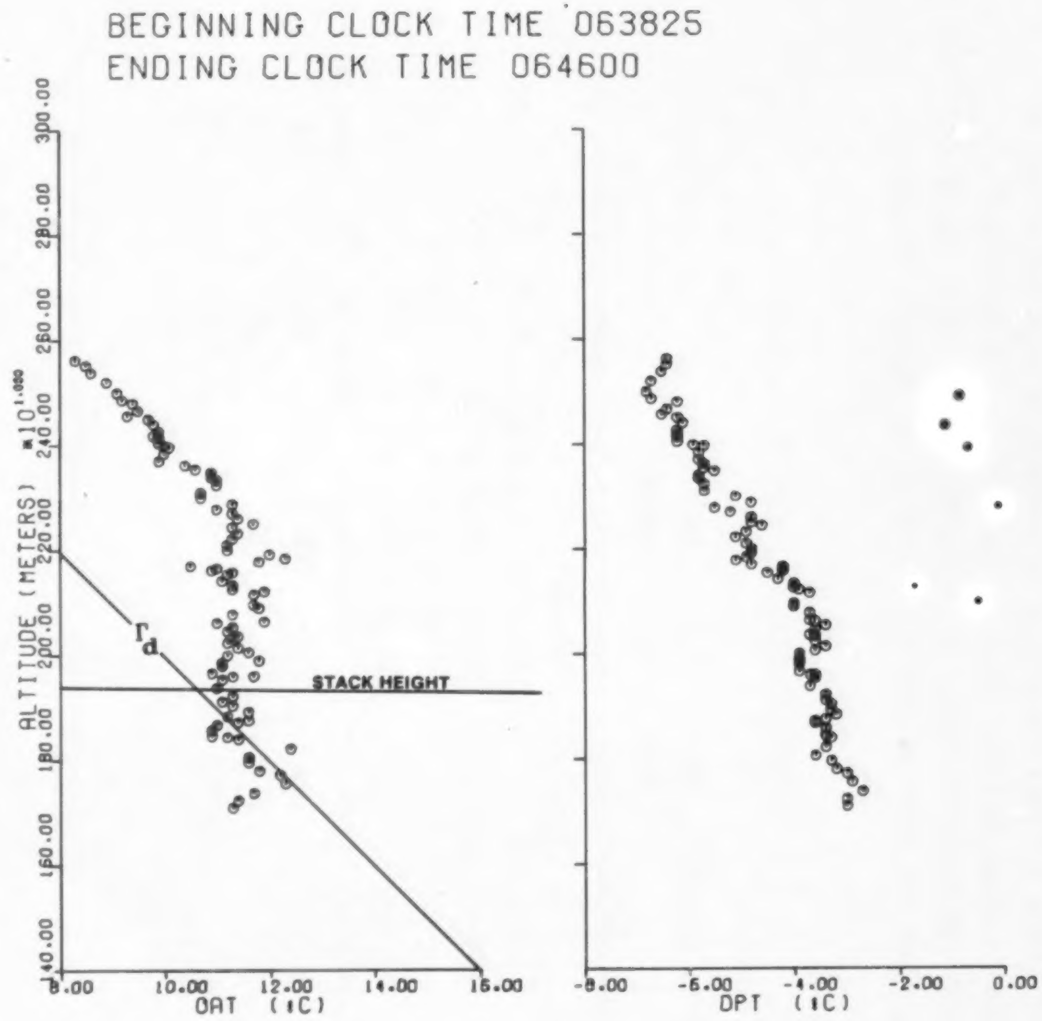

Figure A-27. Temperature and Dewpoint Soundings, 0638 MST, October 13, 1976.

October 14, 1976 063-0819 MST

Neutral conditions were observed at and above stack height with a stable layer below at the start of the mission (Figure A-30). North-northeasterly flow was bringing the plume over the saddle approximately 1.5 km south-southwest of the stack. Impaction was occurring in the vortex that had formed to the lee of the saddle, approximately 1.7 km from the stack. Moderate to severe turbulence was experienced. Spirals were made over the saddle and over the area of impaction. SO_2 concentrations of 0.4 ppm were measured within 30 m of the saddle and 0.6 ppm as low as 15 m above the impaction area. At approximately 0715 MST, the wind shifted and the plume was advected over the valley to the east of the stack.

TABLE A-8
SUMMARY OF MISSION, OCTOBER 14, 1976

1. Butte Weather: 0554 CLR 130/05
0850 CLR 360/07
2. Plant Emissions, SO_2: 0600-0700 11.4×10^9 μg/s
0700-0800 6.2×10^9 μg/s
0800-0900 12.2×10^9 μg/s
3. σ_z, Spiral, SO_2: 87 m/ 5.0 min/ 1.5 km
83 m/ 1.8 min/ 1.7 km
122 m/ 4.3 min/ 1.5 km
4. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0730	1770	010	6
	1950	022	4
0800	1770	346	8
	1950	356	3

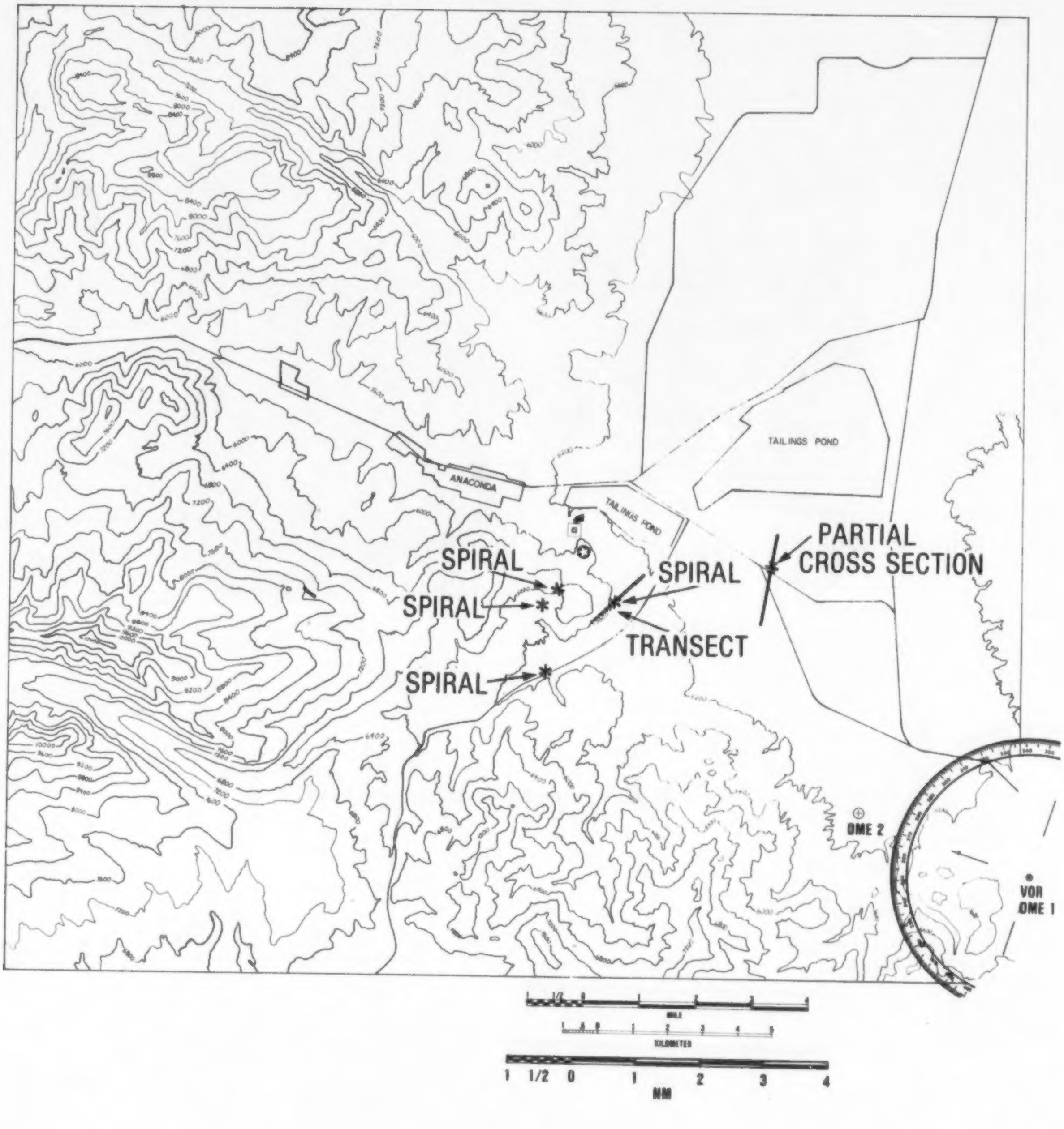

Figure A-28. Sampling Locations, October 14, 1976

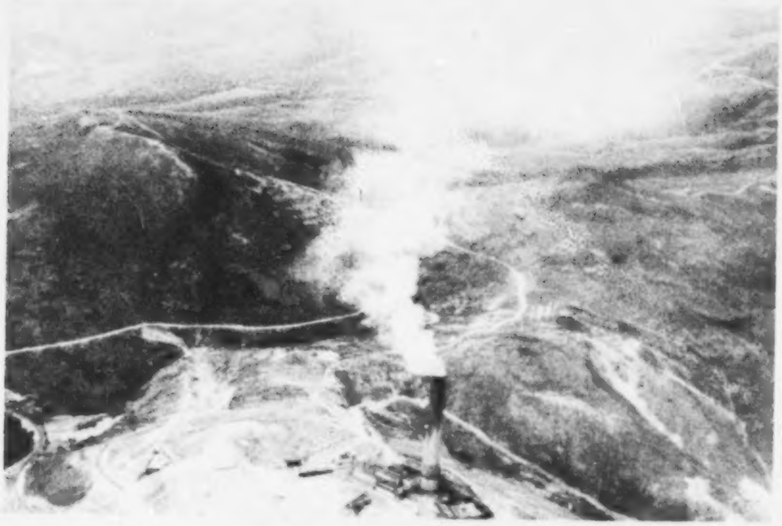

Figure A-29. Plume, October 14, 1976.

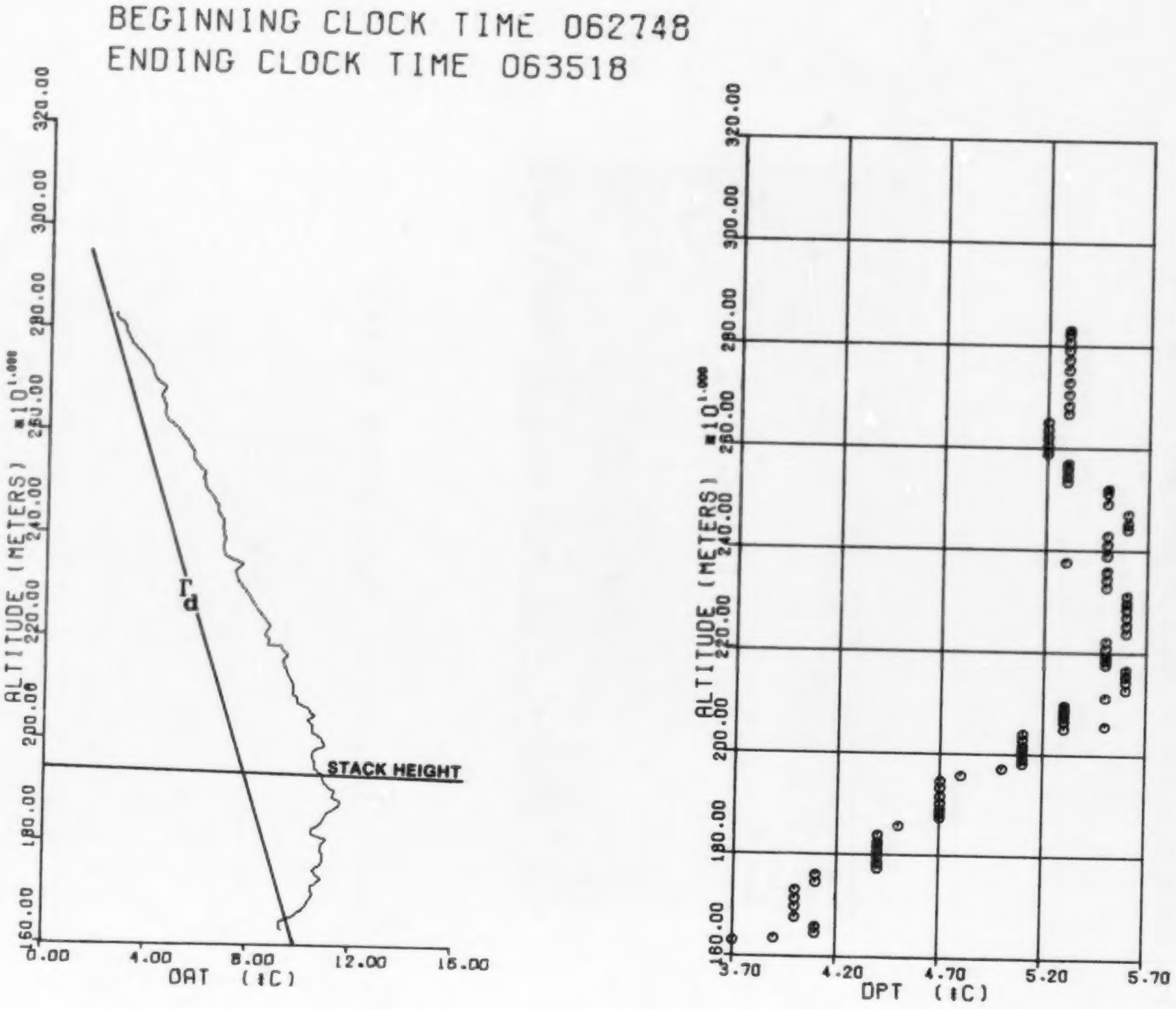

Figure A-30. Temperature and Dewpoint Soundings, 0627 MST, October 14, 1976.

October 15, 1976

No data were collected on this date. However, Figure A-31 is included in this report as an example of extreme fanning under stable conditions. Mechanical turbulence can be noted in this weak stable flow.

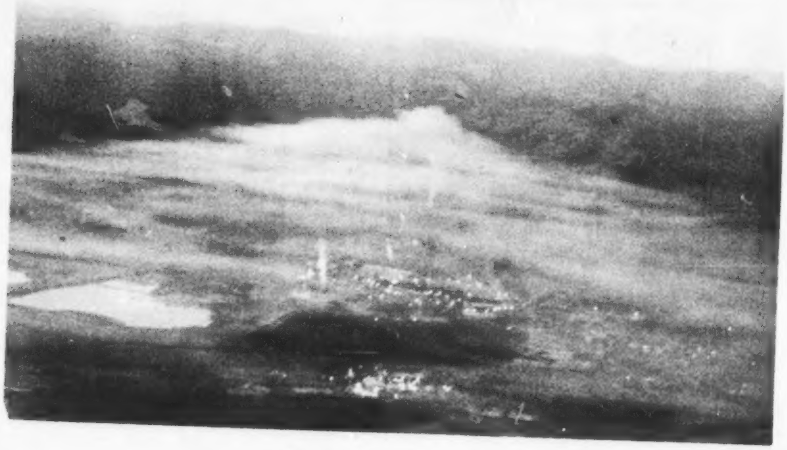

Figure A-31. Plume, October 15, 1976.

October 19, 1976 0629-0851 MST

This flight was conducted under clear skies, light winds and stable conditions (Figures A-34 and A-35). One spiral was made 1.5 km northeast of the stack. This was followed by 12 transects at altitudes ranging from 2040 to 2070 m MSL. A single spiral, followed by two traverses, was made 2.5 km northeast of the stack. The wind then shifted and five spirals each followed by two traverses at the indicated height of the centerline were made 3.8 km southeast of the stack (Figure A-32). Figure A-33 was taken near the end of the mission.

TABLE A-9
SUMMARY OF MISSION, OCTOBER 19, 1976

1. Butte Weather: 0550 CLR 150/05
0850 CLR CLM
2. Plant Emissions, SO_2: 0600-0700 9.9×10^9 µg/s
0700-0800 4.8×10^9 µg/s
0800-0900 8.2×10^9 µg/s
3. Centerline Height/ Distance/ Concentration: 2075 m/ 1.5 km/ 25.7 ppm
4. Three-minute σ_y, SO_2: 143 m/ 40 m/ 11 cases/ 1.5 km
212 m/ 58 m/ 2 cases/ 2.5 km
334 m/ 115 m/ 10 cases/ 3.8 km
5. σ_z, Spiral, SO_2: 47 m/ 1.7 min/ 1.5 km
56 m/ 3.0 min/ 2.5 km
60 m/ 3.0 min/ 3.8 km
32 m/ 2.5 min/ 3.8 km
58 m/ 3.0 min/ 3.8 km
48 m/ 3.0 min/ 3.8 km
63 m/ 4.0 min/ 3.8 km

6. σ_z, Spiral, B_{scat}: 44 m/ 2.5 min/ 3.8 km
53 m/ 3.0 min/ 3.8 km
61 m/ 3.0 min/ 3.8 km
50 m/ 3.0 min/ 3.8 km

7. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0730	1950	336	1
	2020	206	6

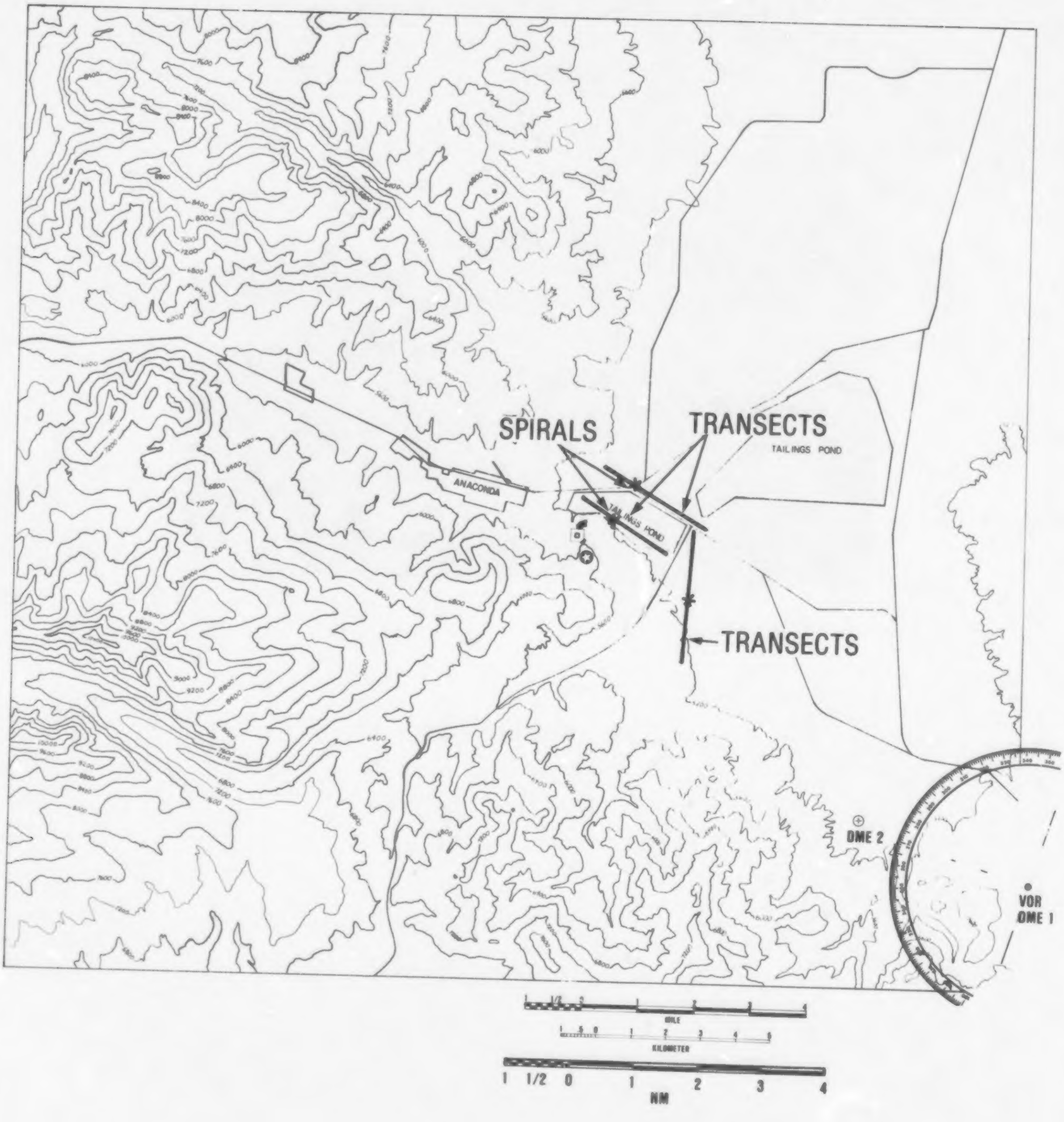

Figure A-32. Sampling Locations, October 19, 1976.

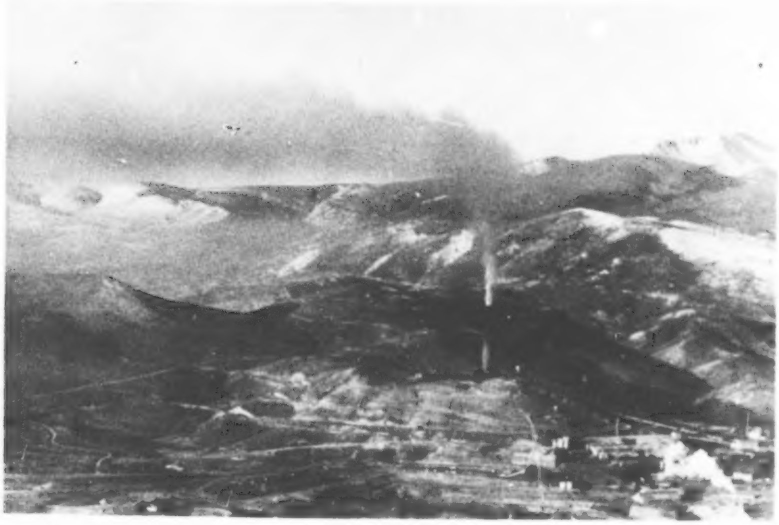

Figure A-33. Plume, October 19, 1976.

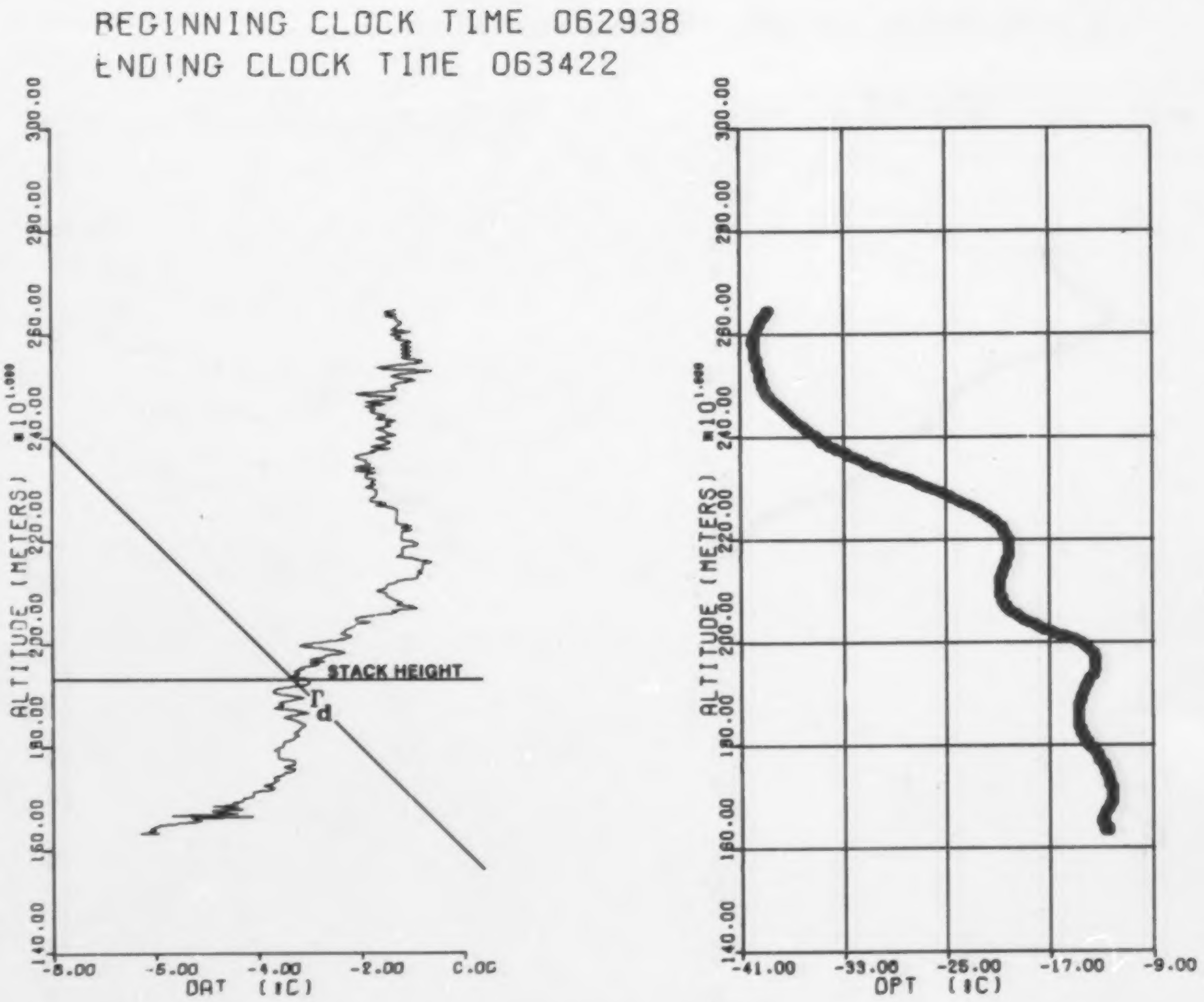

Figure A-34. Temperature and Dewpoint Soundings, 0629 MST, October 19, 1976.

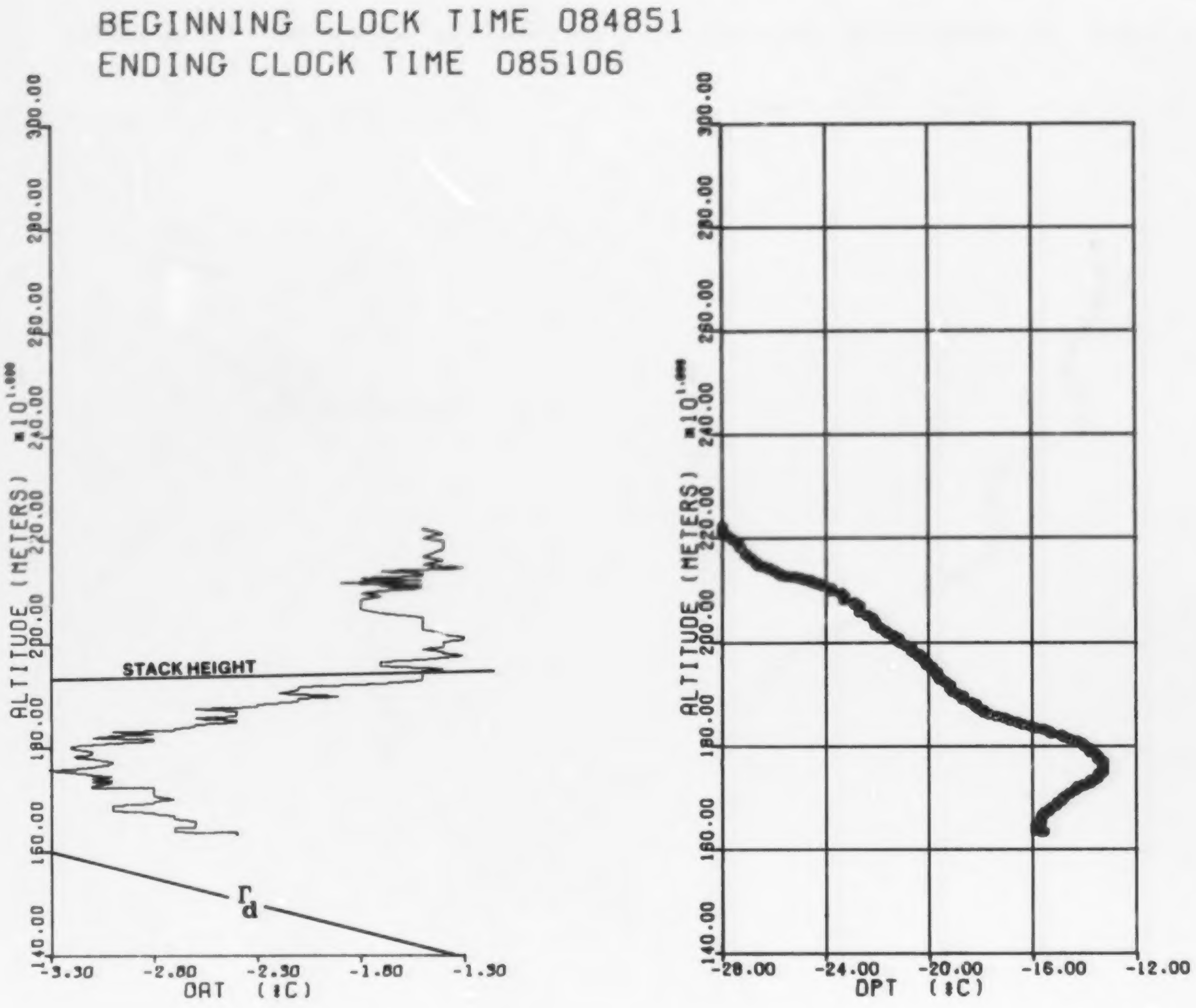

Figure A-35. Temperature and Dewpoint Soundings, 0848 MST, October 19, 1976.

October 20, 1976 0904-1122 MST

Stable conditions persisted throughout the sampling period (Figures A-37 and A-38). Multiple transects were made through the plume at the approximate centerline height at 1.6 km. Multiple spirals were made through the plume at 4.8 km. Each was followed by two traverses at the height of plume centerline (Figure A-36).

TABLE A-10
SUMMARY OF MISSION, OCTOBER 20, 1976

1.	Butte Weather:	0850 CLR 130/03
		1150 CLR 290/05
2.	Plant Emissions, SO_2:	0930-1030 15.8×10^9 μg/s
		1030-1130 10.2×10^9 μg/s
3.	Centerline Height/ Distance/ Concentration:	2000 m/ 4.8 km/ 9.5 ppm
4.	Three-minute σ_y, SO_2:	301 m/ 51 m/ 12 cases/ 1.6 km
		320 m/ 87 m/ 10 cases/ 4.8 km
	Three-minute σ_y, B_{scat}:	328 m/ 39 m/ 12 cases/ 1.6 km
		315 m/ 47 m/ 10 cases/ 4.8 km
5.	σ_z, Spiral, SO_2:	37 m/ 2.0 min/ 1.6 km
		50 m/ 3.0 min/ 4.8 km
		38 m/ 1.8 min/ 4.8 km
		62 m/ 2.9 min/ 4.8 km
		61 m/ 1.9 min/ 4.8 km
		24 m/ 1.2 min/ 4.8 km
		23 m/ 3.2 min/ 4.8 km
6.	σ_z, Spiral, B_{scat}:	58 m/ 3.0 min/ 4.8 km
		29 m/ 1.8 min/ 4.8 km
		61 m/ 2.9 min/ 4.8 km
		55 m/ 1.9 min/ 4.8 km
		24 m/ 1.2 min/ 4.8 km

7. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0730	1950	237	3
0800	1950	218	5
0830	1950	245	8
0900	1950	237	4
0930	1950	259	4
1030	1950	031	11
1100	1950	145	5
1130	1950	225	4

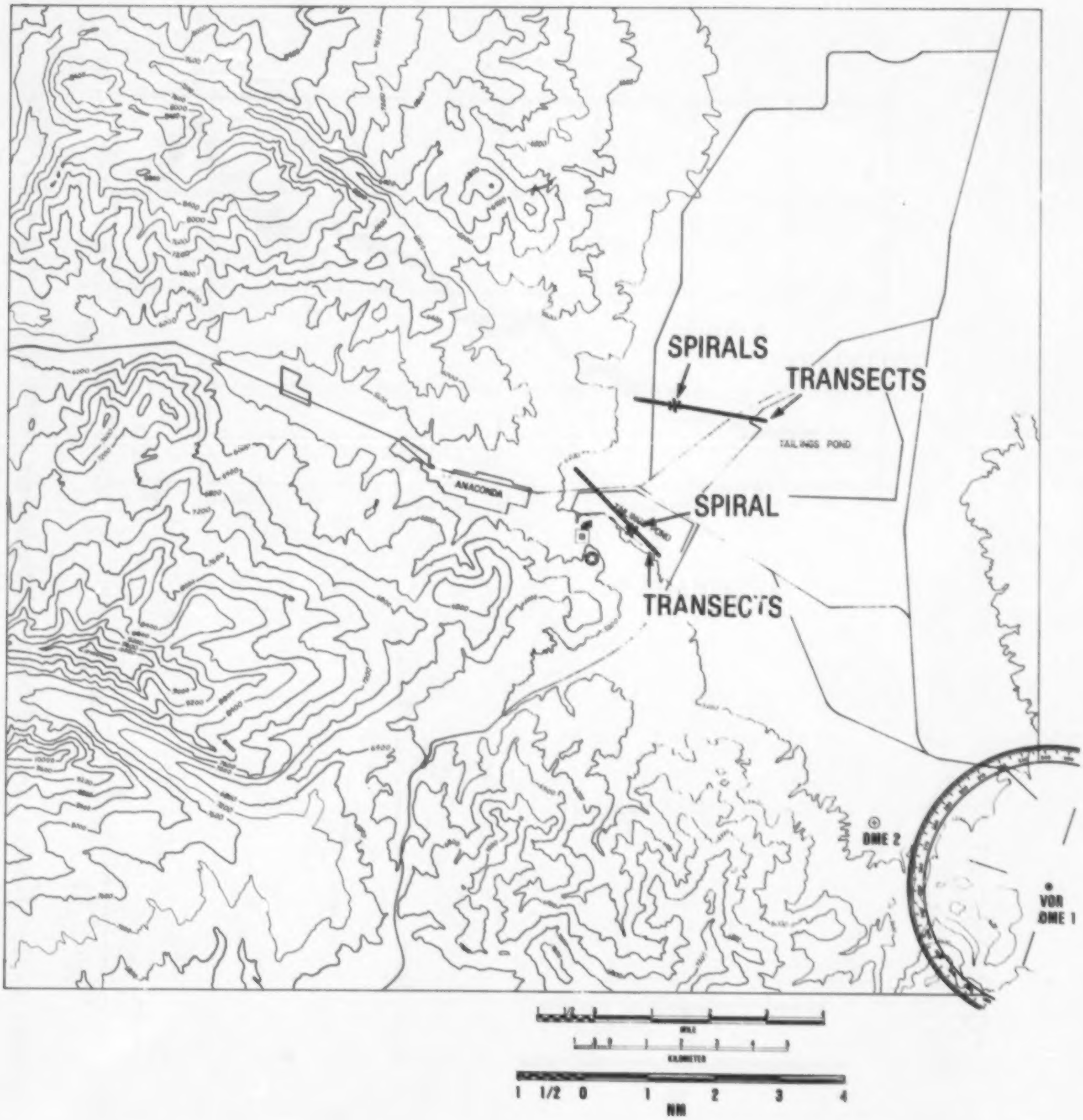

Figure A-36. Sampling Locations, October 20, 1976.

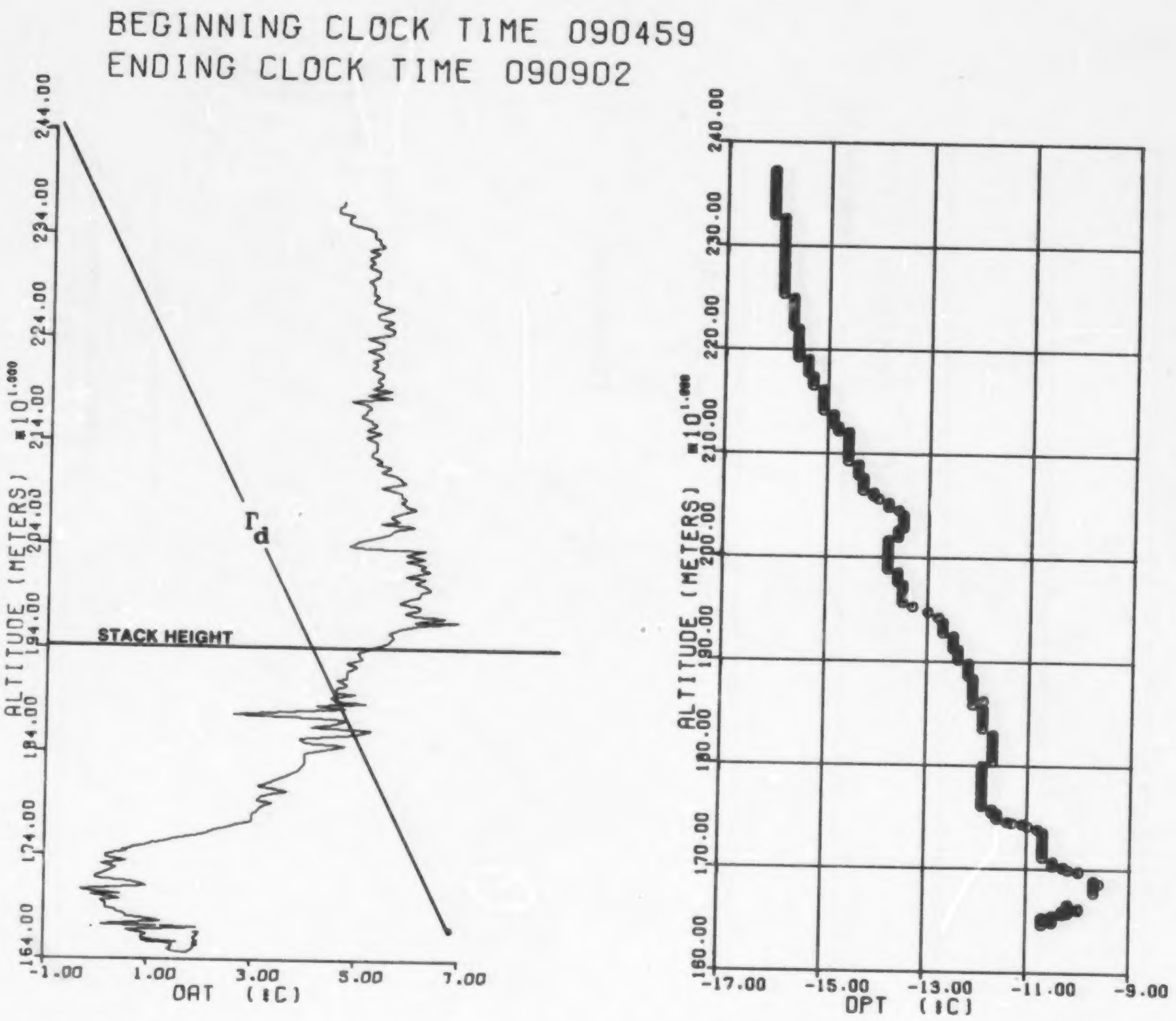

Figure A-37. Temperature and Dewpoint Soundings, 0904 MST, October 20, 1976.

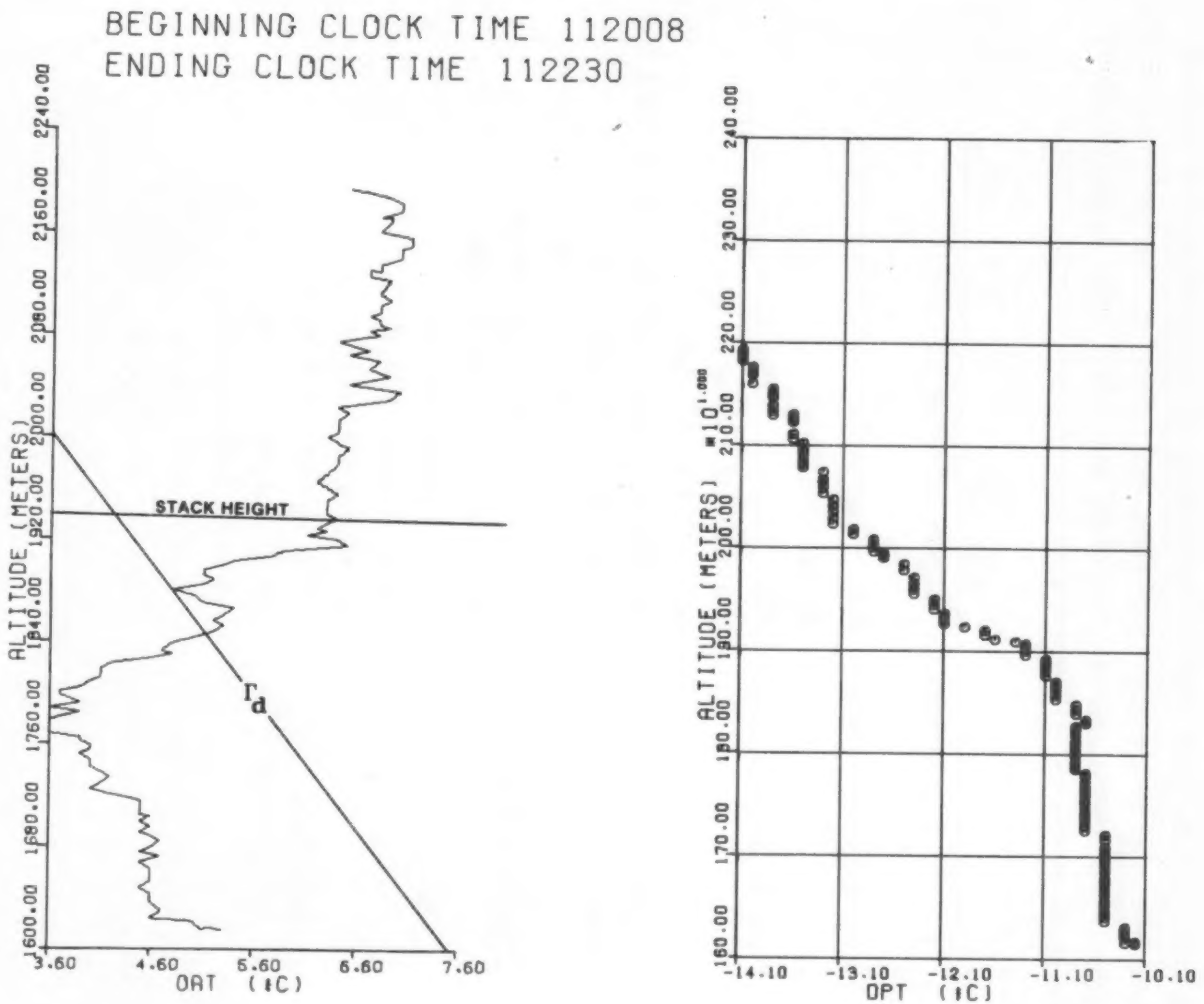

Figure A-38. Temperature and Dewpoint Soundings, 1120 MST, October 20, 1976.

October 21, 1976 0658-0838 MST

Initially, stable conditions existed to approximately 2300 m MSL with near neutral conditions above (Figure A-42). By 0838 MST, near neutral conditions existed from 1900 to 2700 m MSL, while a stable layer existed between 1800 and 1900 m MSL. The plume was fanning at the beginning of the mission (Figure A-40). Later, the plume was lofted into the near neutral layer above 1900 m MSL (Figure A-41).

TABLE A-11
SUMMARY OF MISSION, OCTOBER 21, 1976

1. Butte Weather: 0550 CLR 150/03
   0850 200 THN BRKN CLM
2. Plant Emissions: 0600-0700 13.5×10^9 μg/s
   0700-0800 13.5×10^9 μg/s
   0800-0900 18.2×10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 2316 m/ 1.6 km/ 46.2 ppm
4. Three-minute σ_y, SO_2: 279 m/ 106 m/ 18 cases/ 1.6 km
   491 m/ 70 m/ 6 cases/ 6.4 km
   Three-minute σ_y, B_{scat}: 298 m/ 111 m/ 19 cases/ 1.6 km
   485 m/ 64 m/ 6 cases/ 6.4 km
5. σ_z, Spiral, SO_2: 95 m/ 4.3 min/ 6.4 km
   72 m/ 3.3 min/ 6.4 km
   49 m/ 3.2 min/ 6.4 km
   σ_z, Spiral, B_{scat}: 100 m/ 4.3 min/ 6.4 km
   85 m/ 3.3 min/ 6.4 km
   50 m/ 3.2 min/ 6.4 km
6. σ_z, Cross Section, SO_2: 70 m/ 53 min/ 1.6 km
   σ_z, Cross Section, B_{scat}: 76 m/ 53 min/ 1.6 km

7. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed
0740	1950	233	2
0810	1950	249	4
0840	1950	249	6
0940	1950	229	5
	2310	246	9

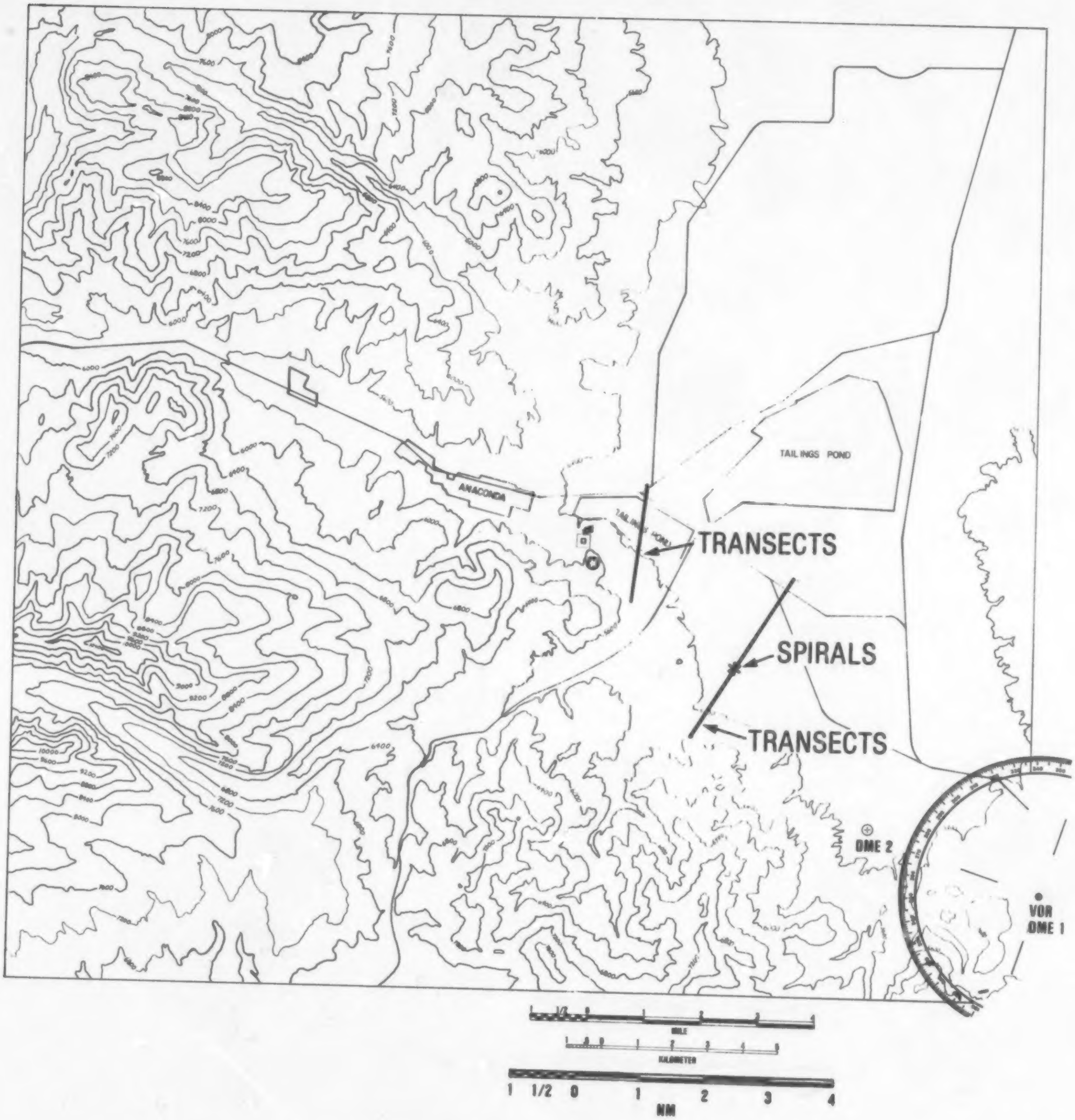

Figure A-39. Sampling Locations, October 21, 1976.

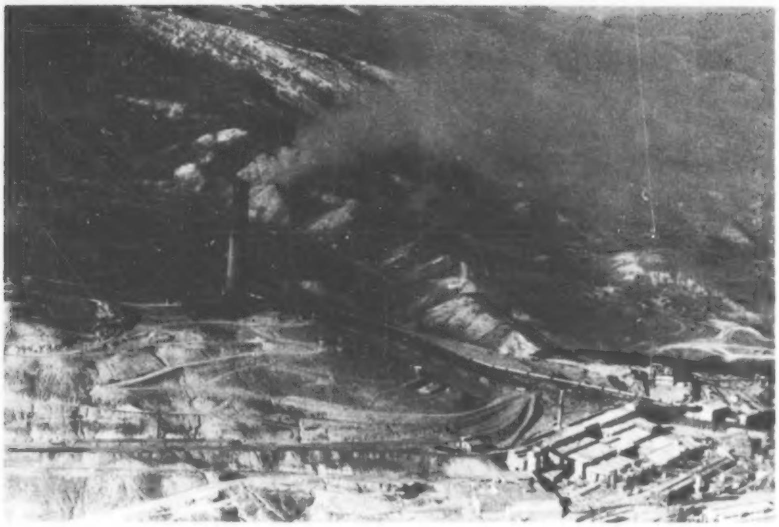

Figure A-40. Plume, October 21, 1976.

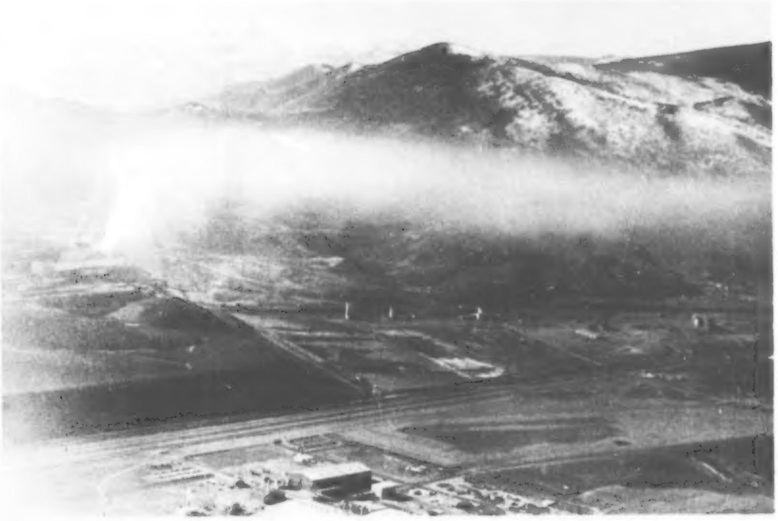

Figure A-41. Plume, October 21, 1976.

BEGINNING CLOCK TIME 063832
ENDING CLOCK TIME 064226

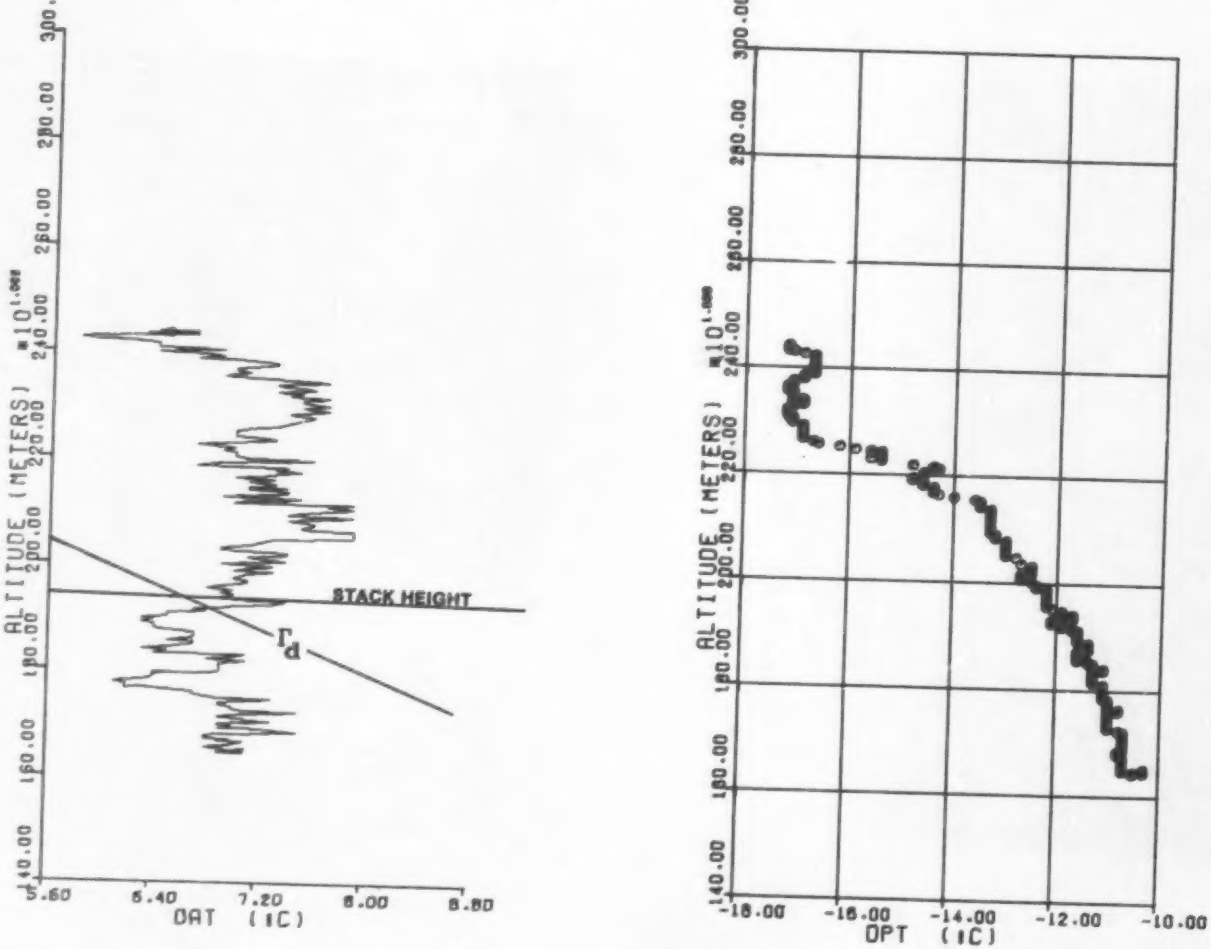

Figure A-42. Temperature and Dewpoint Soundings, 0638 MST, October 21, 1976.

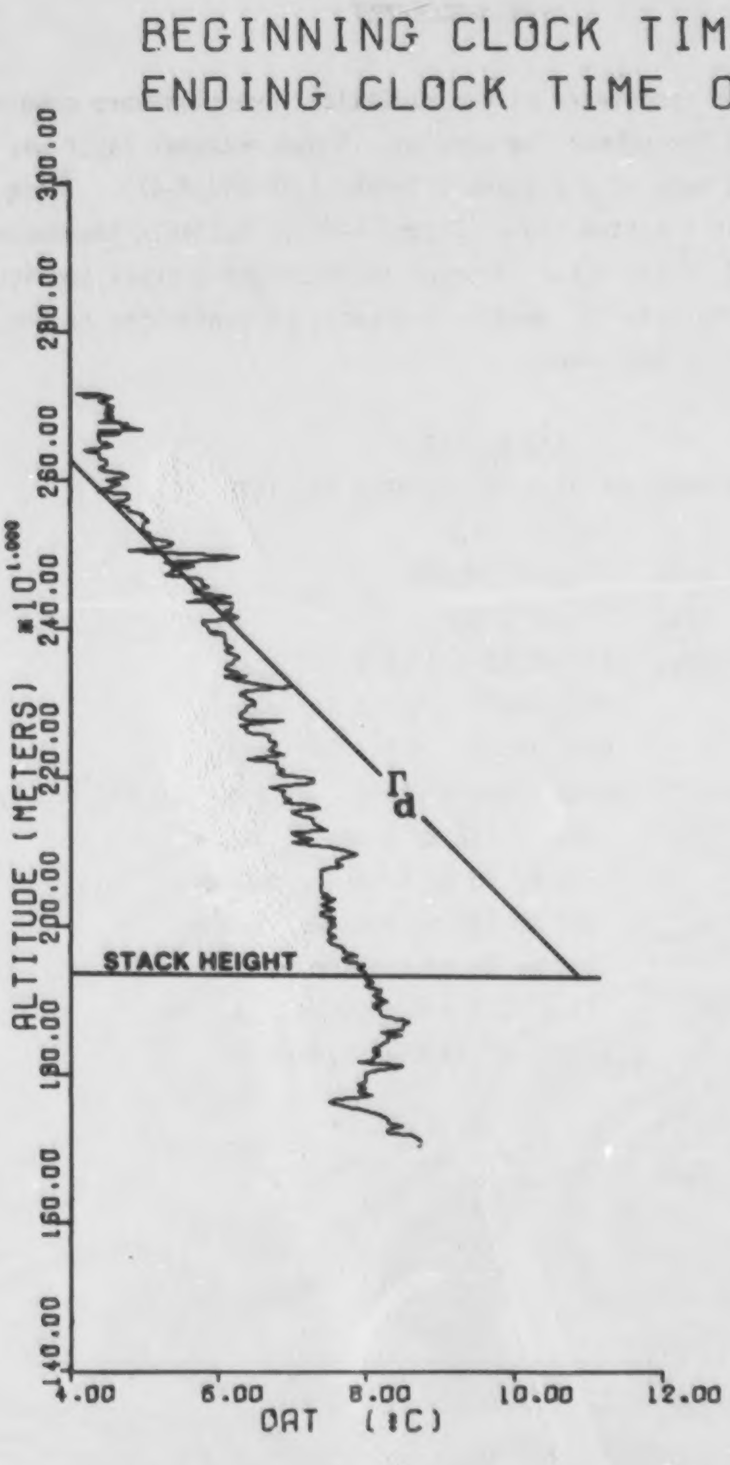

Figure A-43. Temperature Sounding, 0833 MST, October 21, 1976.

October 22, 1976 0816-1035 MST

Stable conditions associated with a radiation inversion were observed near the stack height throughout the mission. A near-neutral layer was immediately above the tope of the stack (Figures A-46 and A-47). These conditions resulted in a lofted plume (Figure A-45). Multiple transects were made 3.0 km northeast of the stack in order to construct a cross section of the plume. Multiple spirals followed by transects at centerline height were made 5.0 km northeast of the stack.

TABLE A-12
SUMMARY OF MISSION, OCTOBER 22, 1976

1. Butte Weather: 0555 CLR 160/03
   0850 CLR CLM
2. Plant Emissions, SO_2: 0700-0800 13.0×10^9 μg/s
   0800-0900 15.1×10^9 μg/s
   0900-1000 16.1×10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 2714 m/ 3.0 km/ 5.5 ppm
4. Three-minute σ_y, SO_2: 336 m/ 112 m/ 9 cases/ 3.0 km
   340 m/ 38 m/ 6 cases/ 5.0 km
   Three-minute σ_y, B_{scat}: 361 m/ 187 m/ 9 cases/ 3.0 km
   358 m/ 62 m/ 6 cases/ 5.0 km
5. σ_z, Spiral, B_{scat}: 41 m/ 2.7 min/ 5.0 km
6. σ_z, Cross Section, B_{scat}: 139 m/ 39 min/ 3.0 km

7. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0740	1950	216	5
	2520	251	3
0810	1950	214	4
	2520	273	3
0840	1950	222	3
	2520	262	4
0910	1950	211	4
	2520	253	3
0940	1950	211	4
	2520	266	6
1010	1950	209	9
	2520	259	5

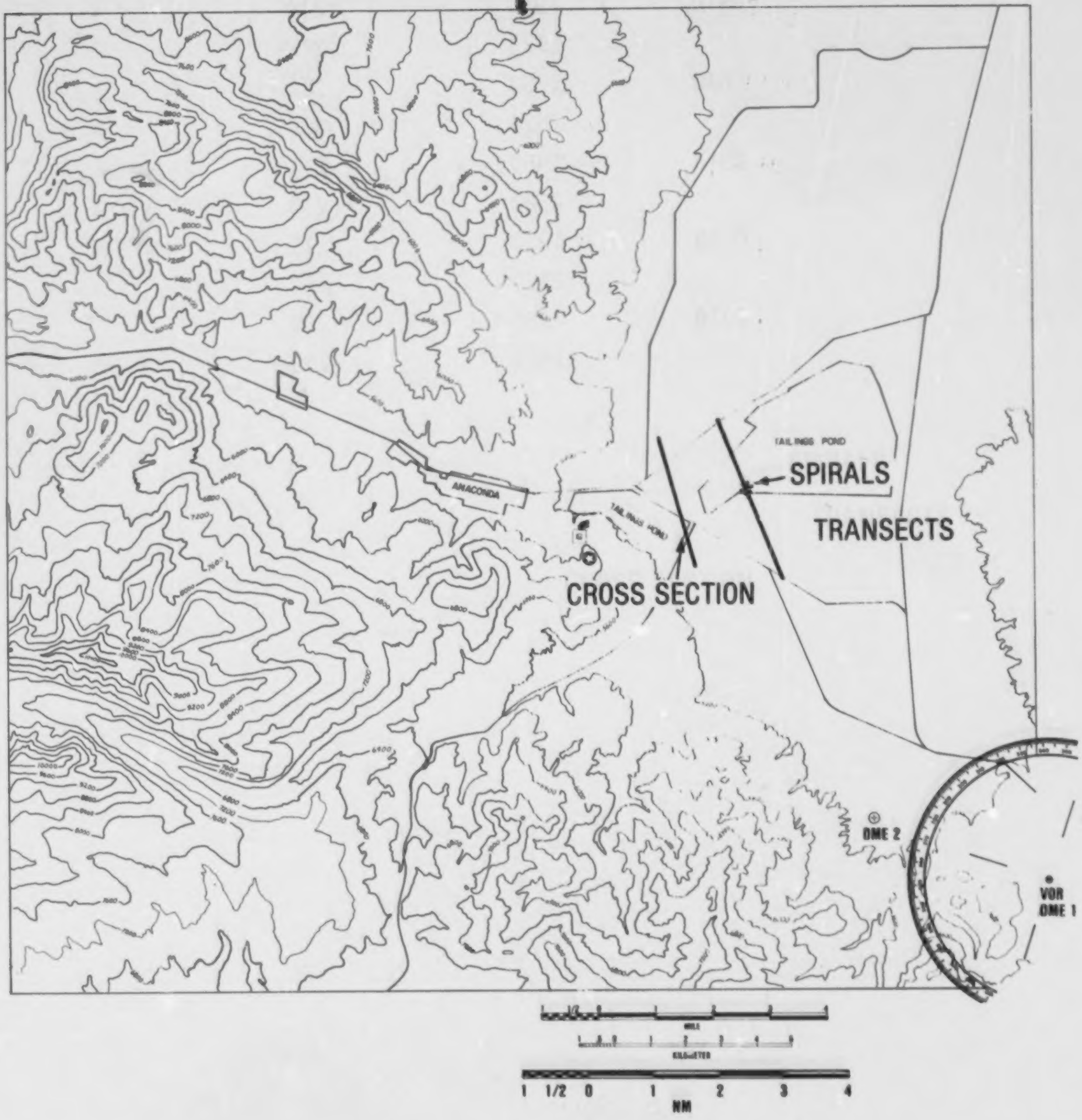

Figure A-44. Sampling Locations, October 21, 1976.

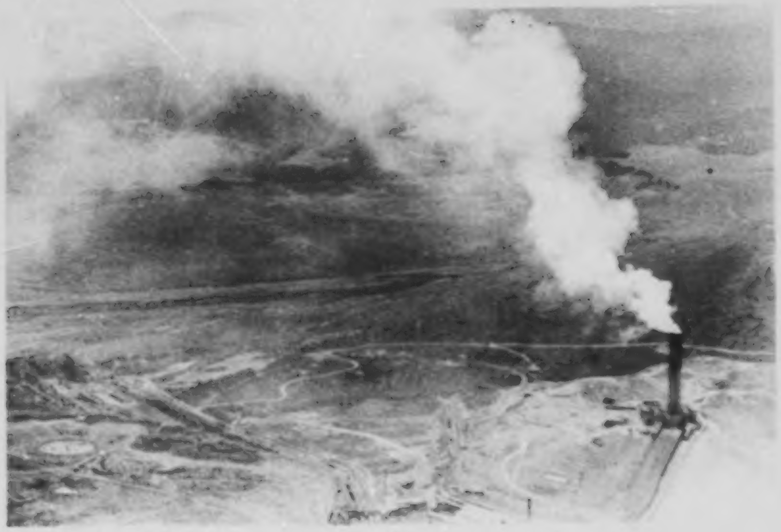

Figure A-45. Plume, October 22, 1976.

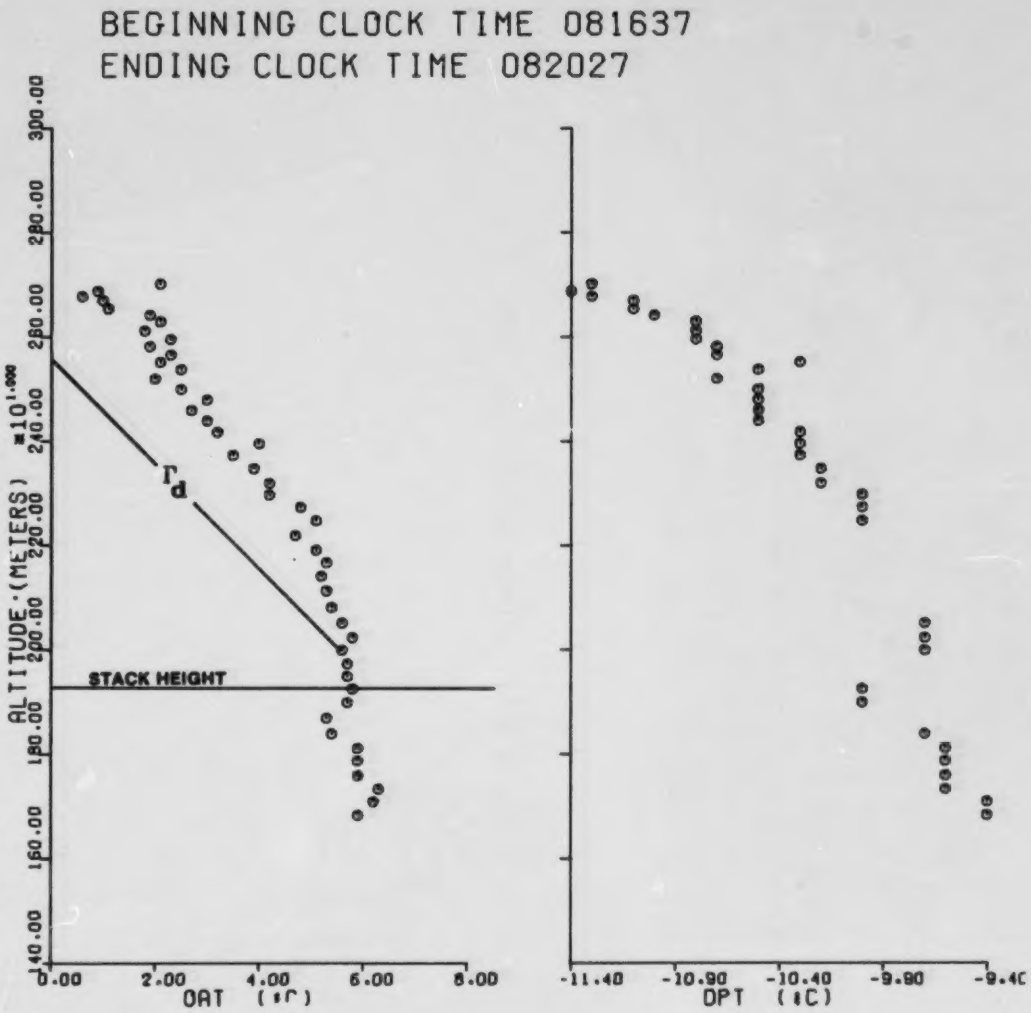

Figure A-46. Temperature and Dewpoint Soundings, 0816 MST, October 22, 1976.

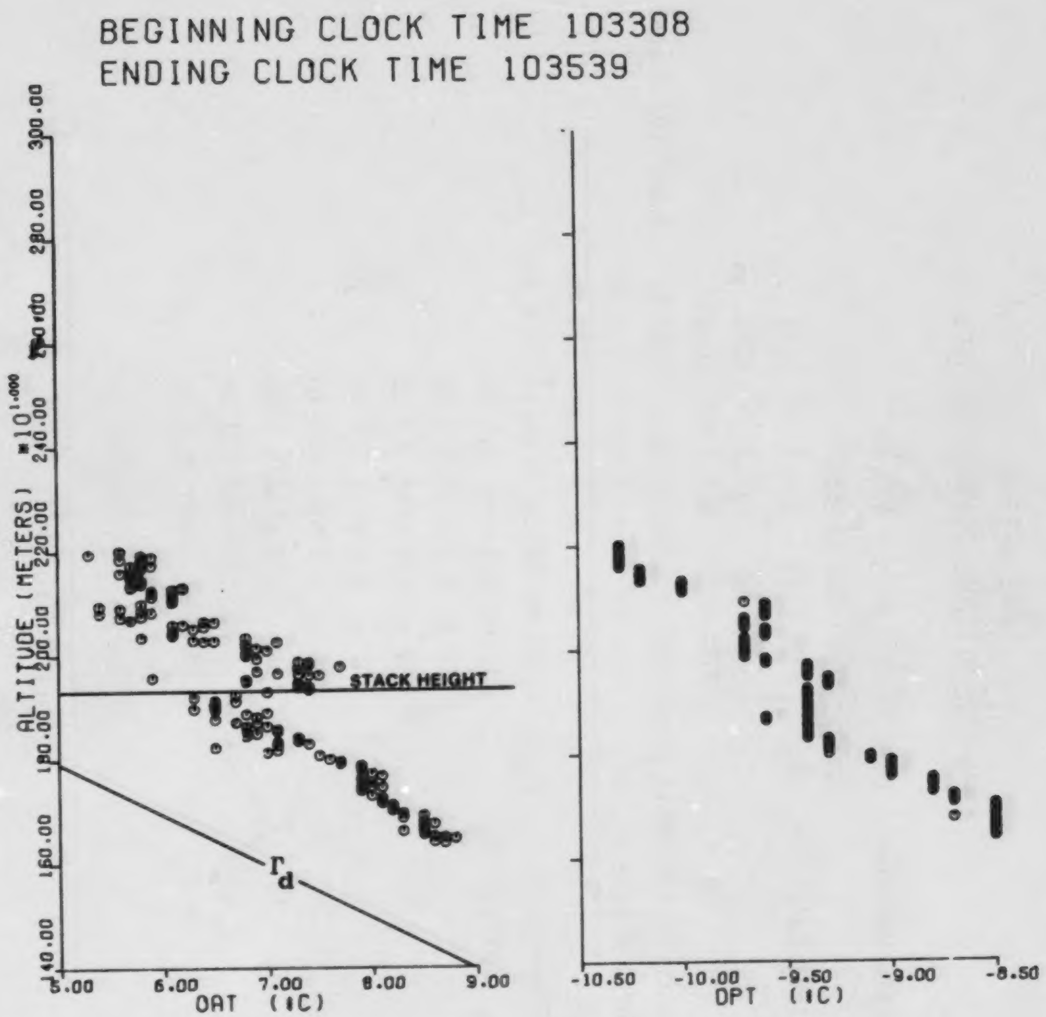

Figure A-47. Temperature and Dewpoint Soundings, 1033 MST, October 22, 1976.

October 26, 1976 0650-0850 MST

Neutral conditions were observed (Figure A-50). A cross section was constructed 1.4 km east of the stack. In addition, multiple spirals, each followed by two transects at plume centerline height, were conducted 5.3 km southeast of the stack (Figure A-48).

TABLE A-13

SUMMARY OF MISSION, OCTOBER 26, 1976

1.	Butte Weather:	0553 50 BRKN 120/04
		0850 80 SCT CLM
2.	Plant Emissions, SO_2:	0630-0730 9.1 X 10^9 μg/s
		0730-0830 9.7 X 10^9 μg/s
		0830-0930 5.8 X 10^9 μg/s
3.	Centerline Height/ Distance/ Concentration:	≈2100 m/ 1.4 km/ 19/ 1 ppm
4.	Three-minute σ_y, SO_2:	151 m/ 90 m/ 4 cases/ 1.4 km
		289 m/ 90 m/ 9 cases/ 5.3 km
	Three-minute σ_y, B_{scat}:	143 m/ 107 m/ 4 cases/ 1.4 km
5.	σ_z, Spiral, SO_2:	75 m/ 3.0 min/ 5.3 km
		65 m/ 2.3 min/ 5.3 km
		94 m/ 3.8 min/ 5.3 km
		81 m/ 5.5 min/ 5.3 km
		65 m/ 2.3 min/ 5.3 km
6.	σ_z, Spiral, B_{scat}:	64 m/ 2.3 min/ 5.3 km
		61 m/ 2.3 min/ 5.3 km
		84 m/ 3.8 min/ 5.3 km

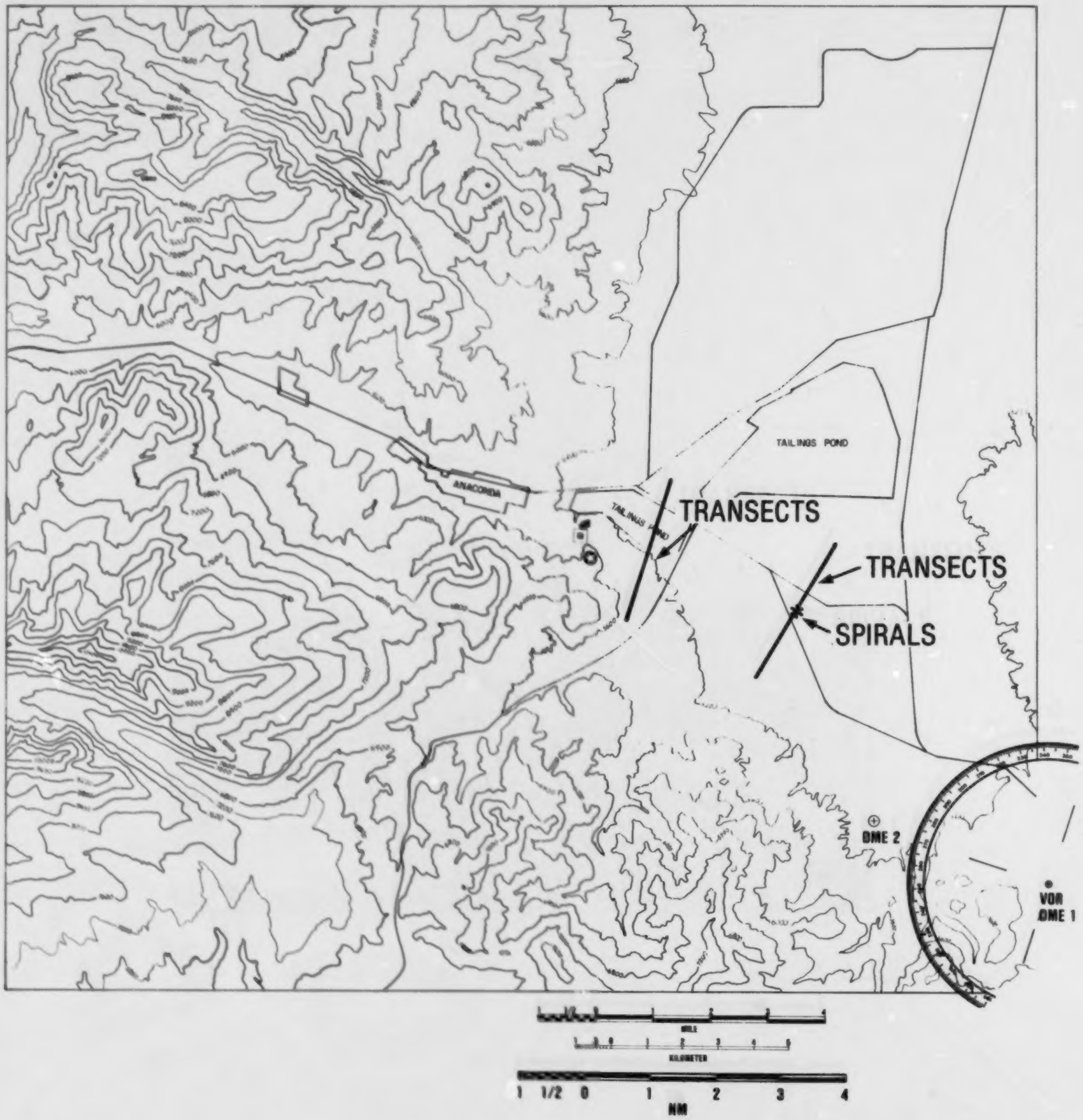

Figure A-48. Sampling Locations, October 26, 1976.

7. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0745	1950	299	7
	2100	299	9
0849	1950	315	5
	2100	304	7

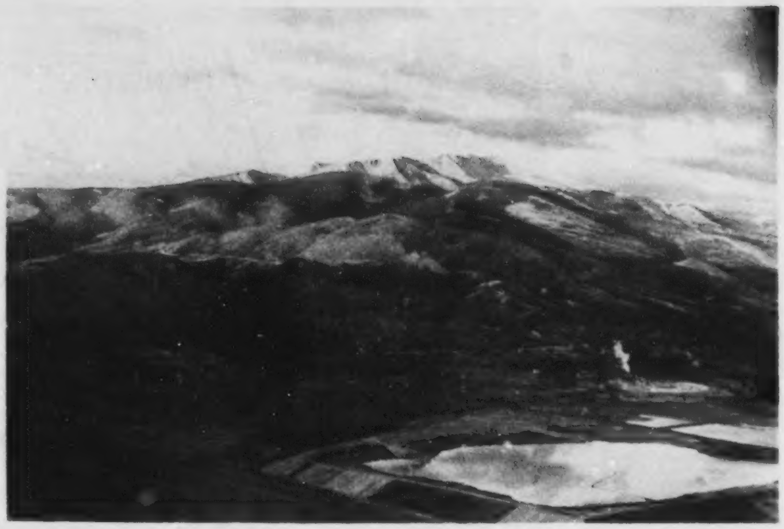

Figure A-49. Plume, October 26, 1976.

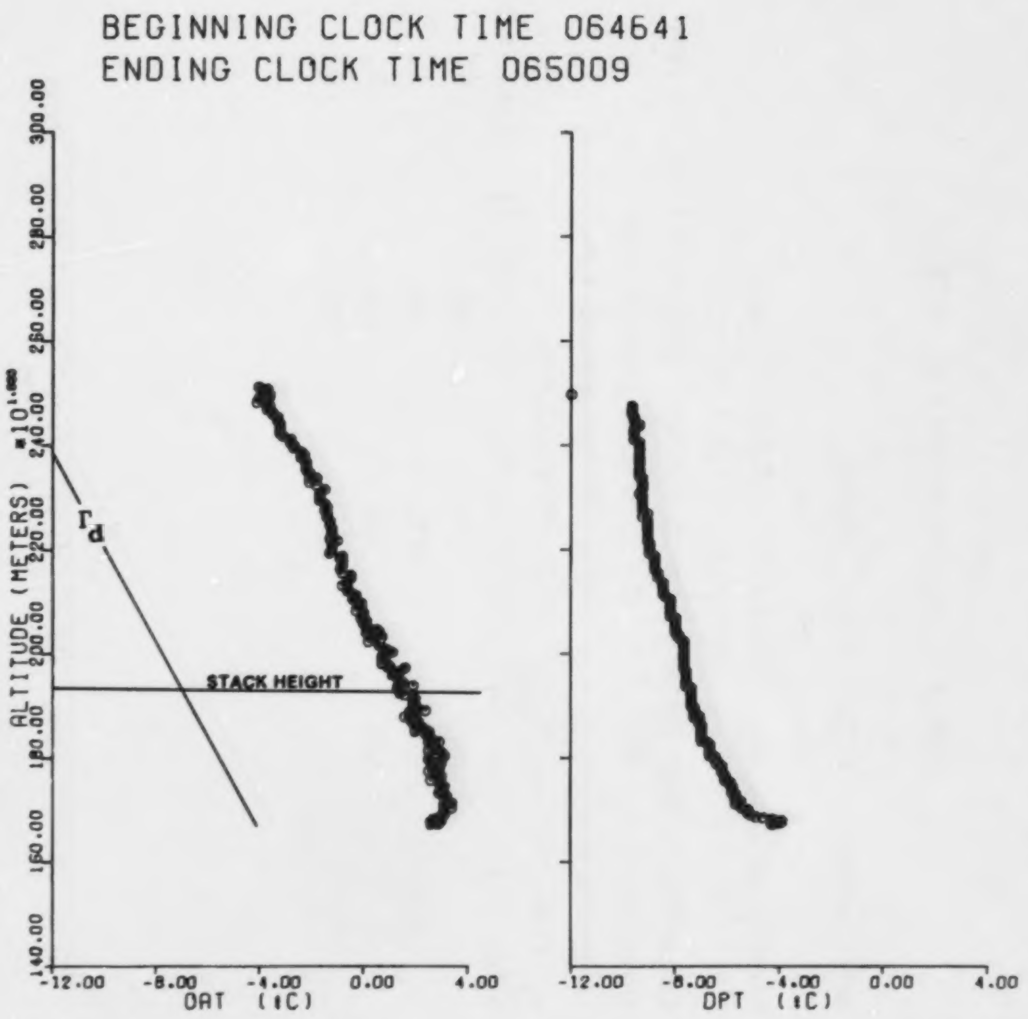

Figure A-50. Temperature and Dewpoint Soundings, 0646 MST, October 26, 1976.

October 27, 1976 0614-0805 MST

Stable conditions were observed near the stack height throughout the mission (Figures A-53 and A-54). An abortive attempt was made to construct a cross section 19 km northeast of the stack. A cross section was constructed 3.4 km east northeast of the stack (Figure A-51).

TABLE A-14
SUMMARY OF MISSION, OCTOBER 27, 1976

1. Butte Weather: 0555 CLR 160/03
   0850 CLR CLM
2. Plant Emissions, SO_2: 0630-0730 14.0×10^9 μg/s
   0730-0830 6.6×10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 2256 m/ 3.4 km/ 2.6 ppm
4. Three-minute σ_y, SO_2: 514 m/167 m/13 cases/3.4 km
5. Three-minute σ_y, B_{scat}: 471 m/141 m/9 cases/3.4 km
6. σ_z, Cross Section, B_{scat}: 117 m/42 min/3.4 km
7. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0745	1950	240	5
	2250	269	7
0815	1950	236	3
	2250	288	6

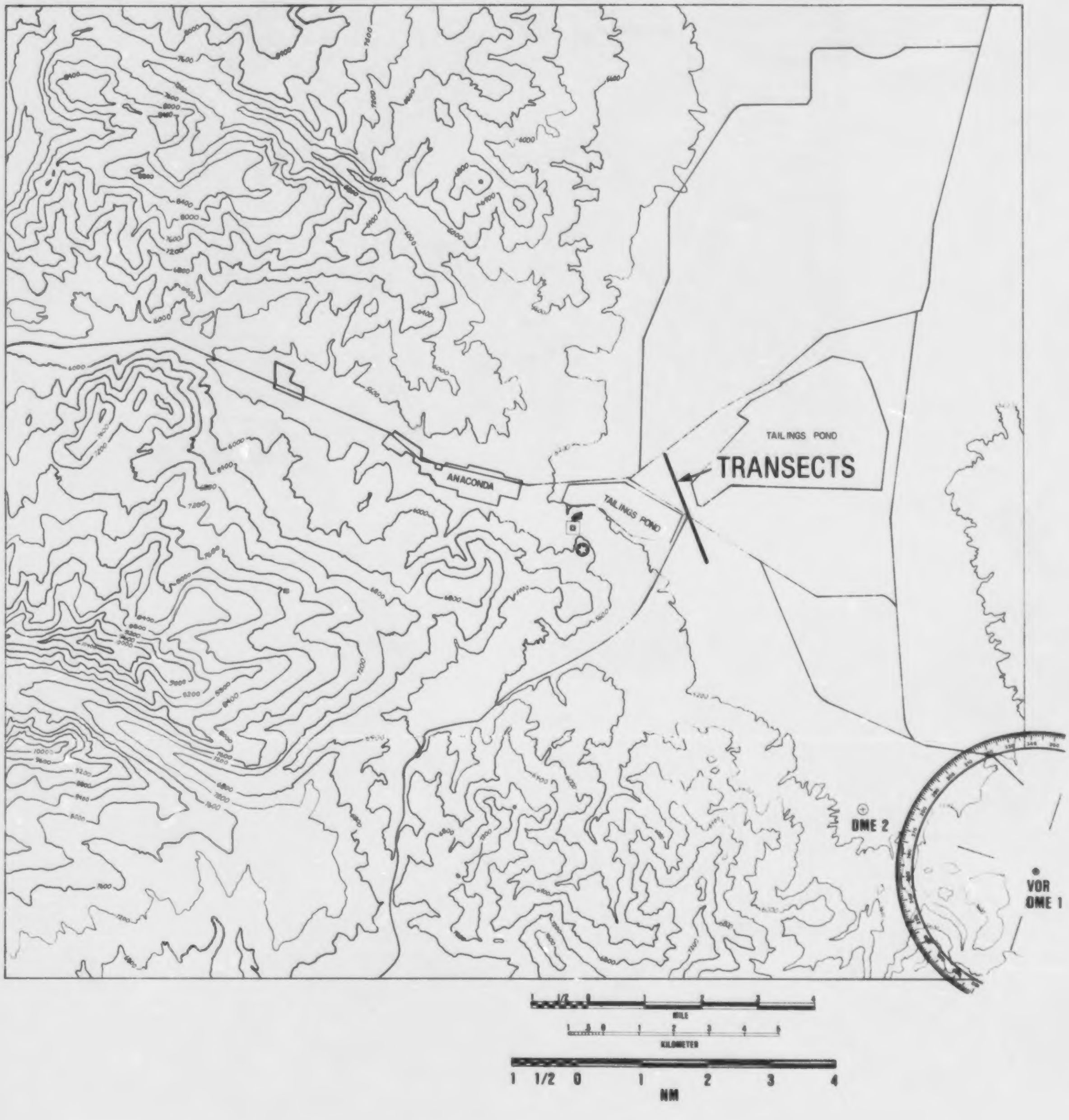

Figure A-51. Sampling Locations, October 27, 1976.

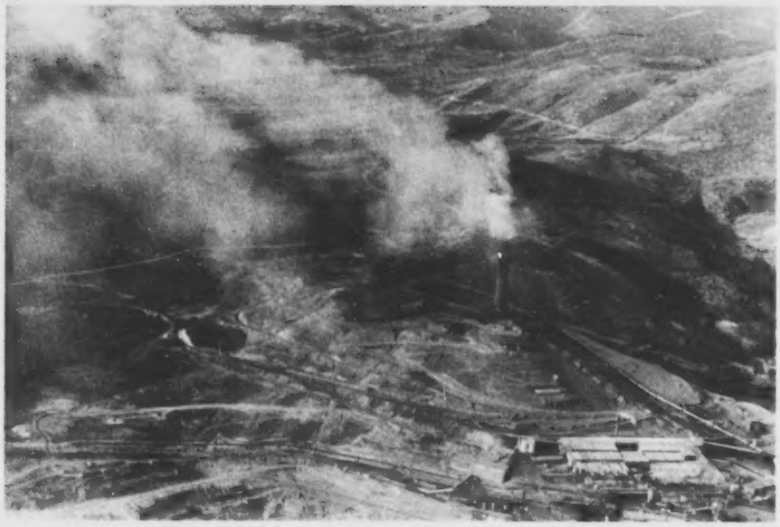

Figure A-52. Plume, October 27, 1976.

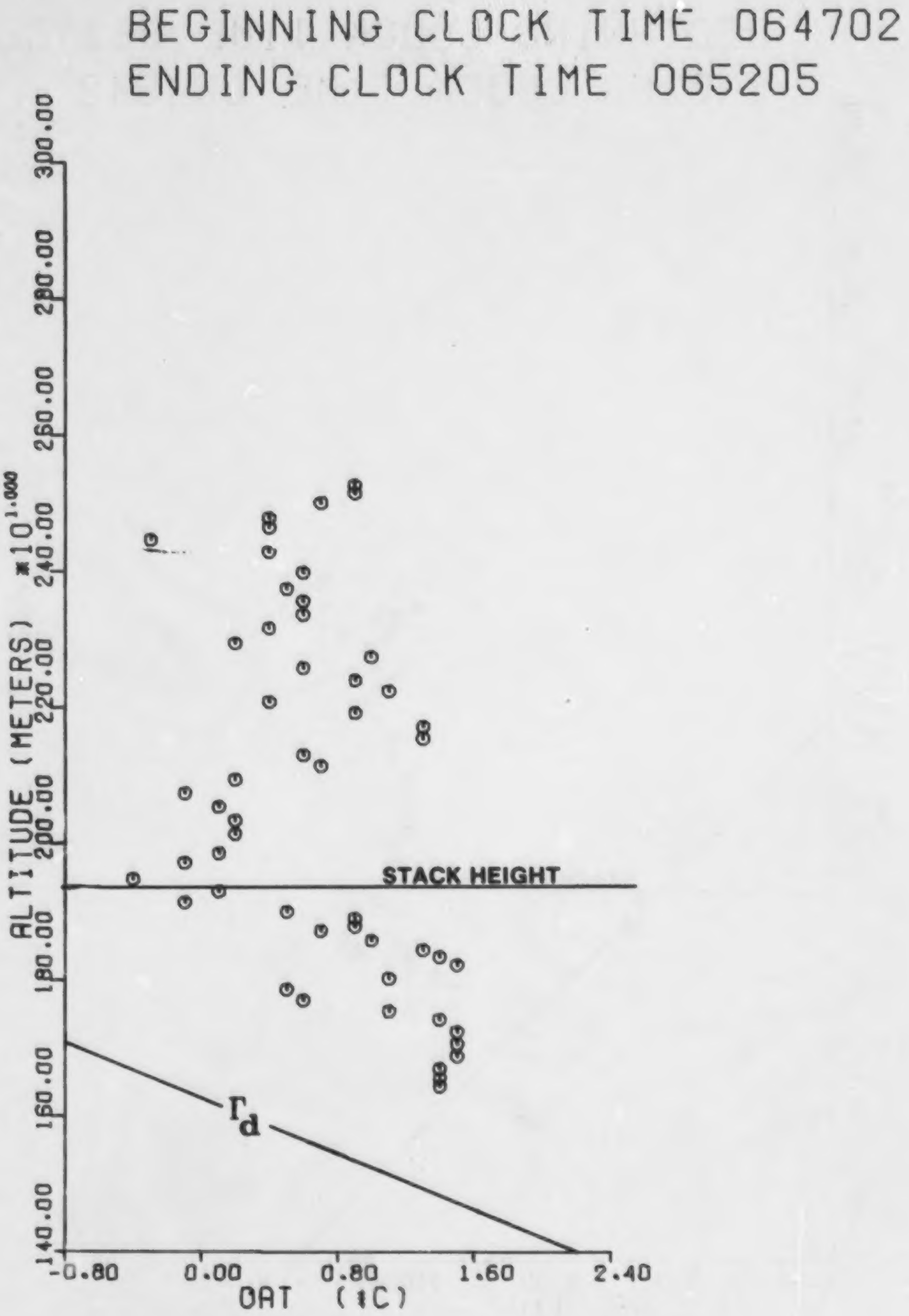

Figure A-53. Temperature Sounding, 0647 MST, October 27, 1976.

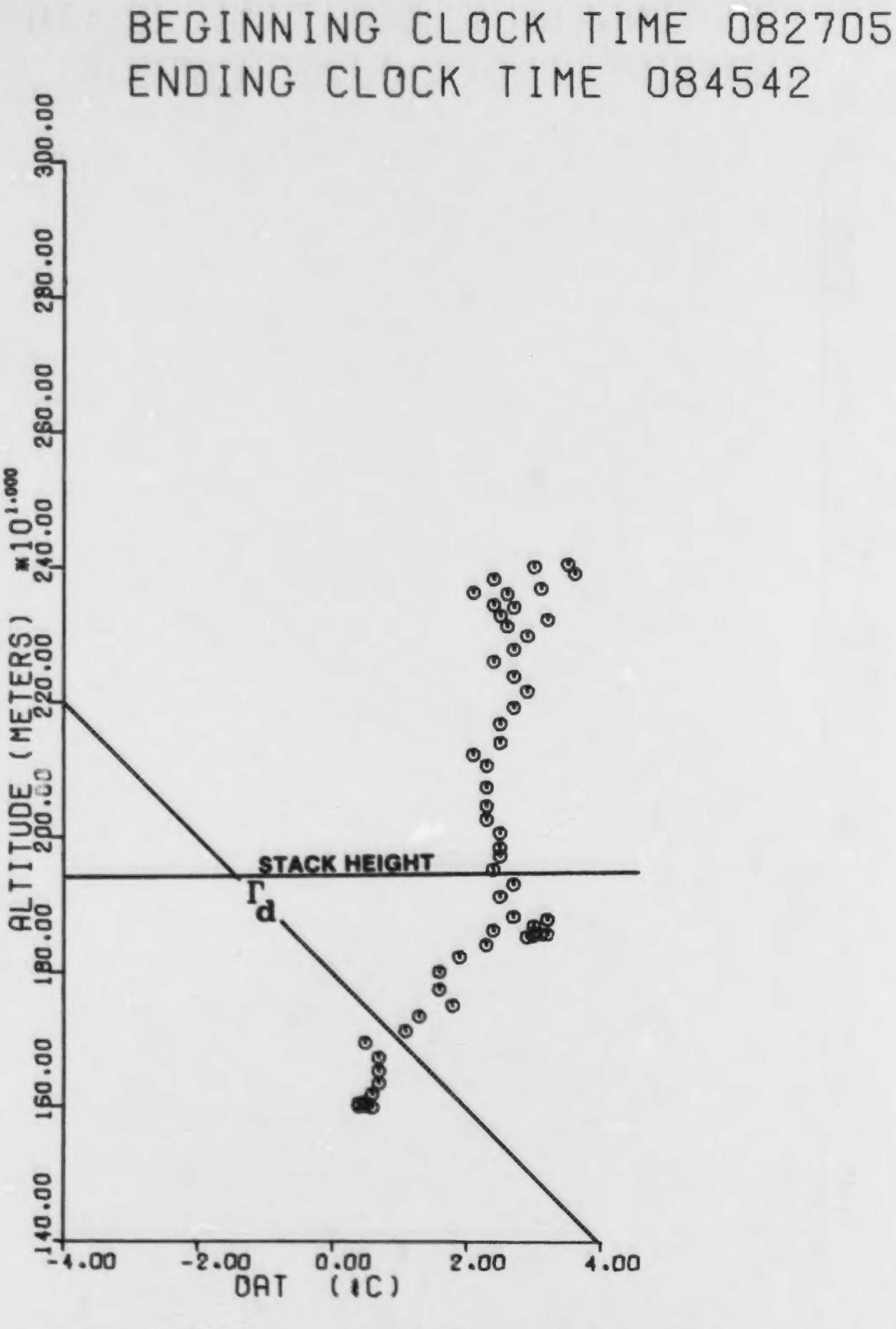

Figure A-54. Temperature Sounding, 0827 MST, October 27, 1976.

October 28, 1976 0641-0845 MST

Moderate, appparently katabatic, flow generated stable conditions at stack height (Figures A-58 and A-59). The plume was frequently observed impacting upon the surface within 1 km of the stack (Figures A-56 and A-57). Turbulent conditions made measurements in the vertical difficult. Transects were made through the plume at 0.8, 1.0, and 2.8 km.

TABLE A-15
SUMMARY OF MISSION, OCTOBER 28, 1976

1. Butte Weather: 0650 250 SCT 160/05
   0950 250 SCT CLM
2. Plant Emissions, SO_2: 0630-0730 14.6×10^9 μg/s
   0730-0830 12.4×10^9 μg/s
   0830-0930 11.6×10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 1827 m/ 0.8 km/26.0 ppm
4. Three-minute σ_y, SO_2: 327 m/220 m/8 cases/0.8 km
   228 m/ 57 m/5 cases/1.0 km
   447 m/165 m/4 cases/2.8 km
5. Three-minute σ_y, B_{scat}: 270 m/94 m/8 cases/0.8 km
   271 m/83 m/5 cases/1.0 km
   446 m/190 m/4 cases/2.8 km
6. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (^{o})	Speed (m/s)
0747	1830	223	10
	1950	239	6
0817	1830	227	10
	1950	229	8
0847	1830	221	10
	1950	222	8

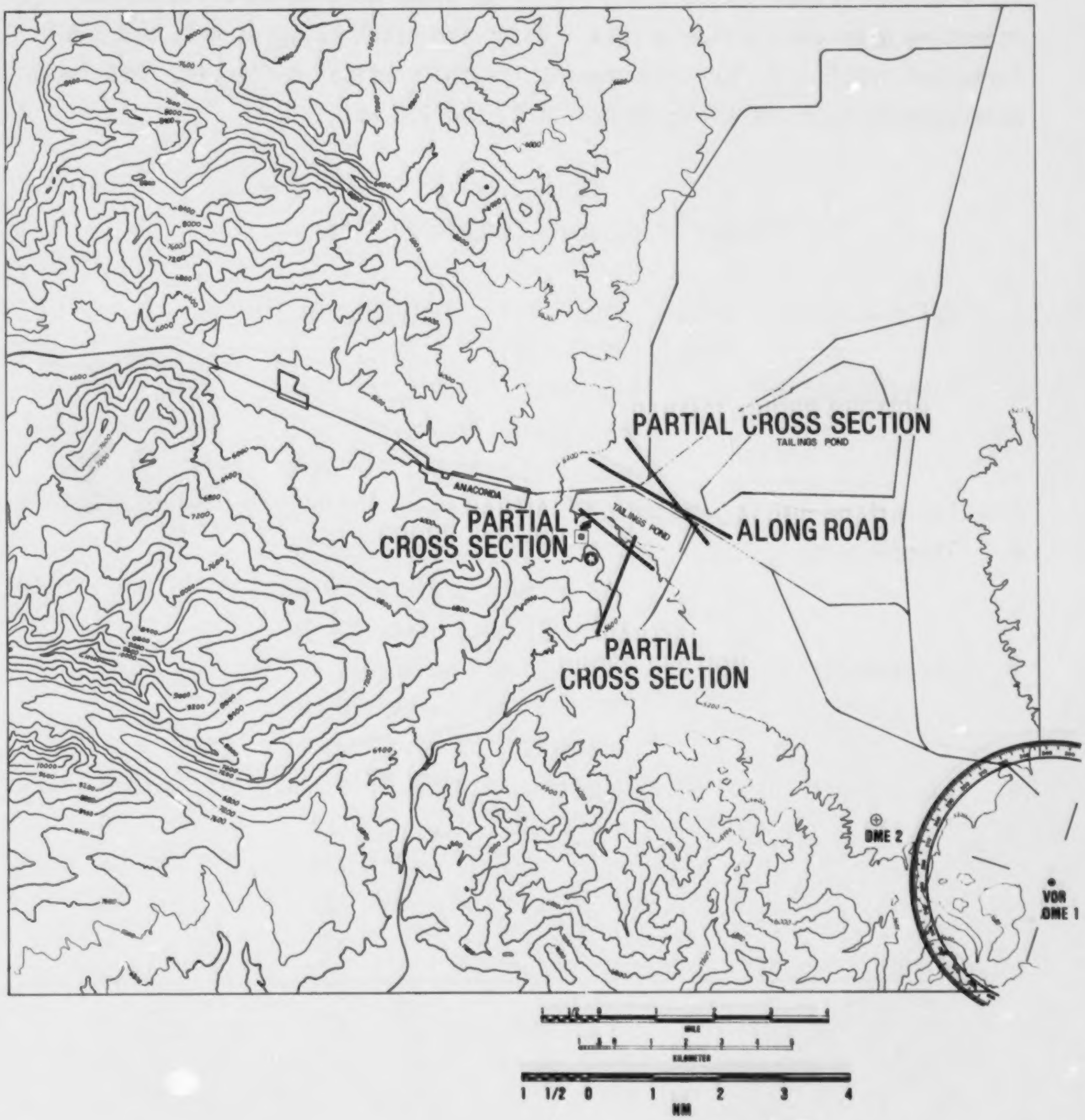

Figure A-55. Sampling Locations, October 28, 1976.

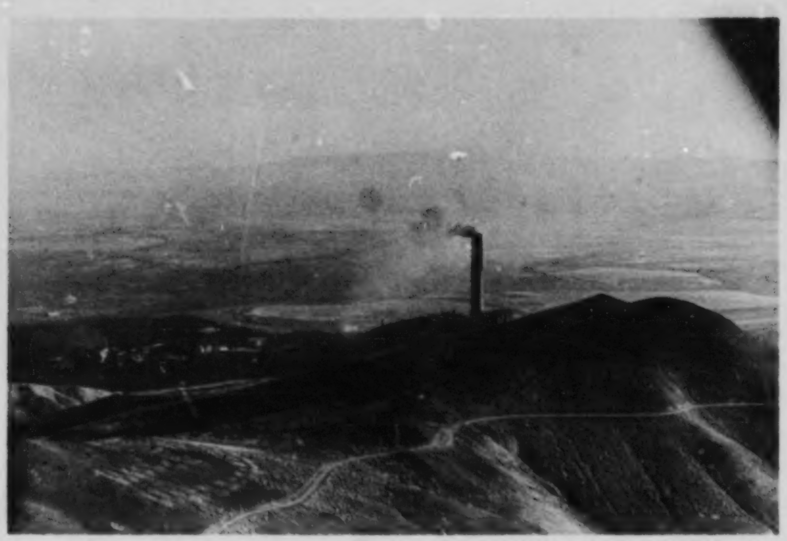

Figure A-56. Plume, October 28, 1976.

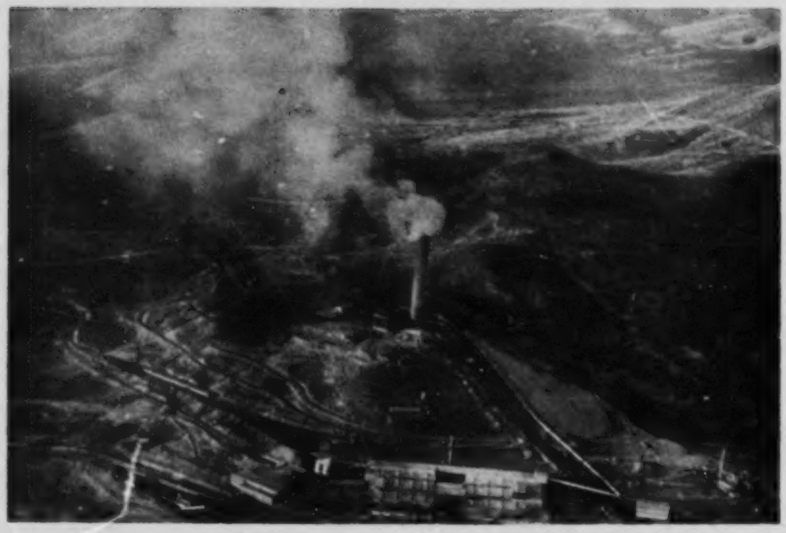

Figure A-57. Plume, October 28, 1976.

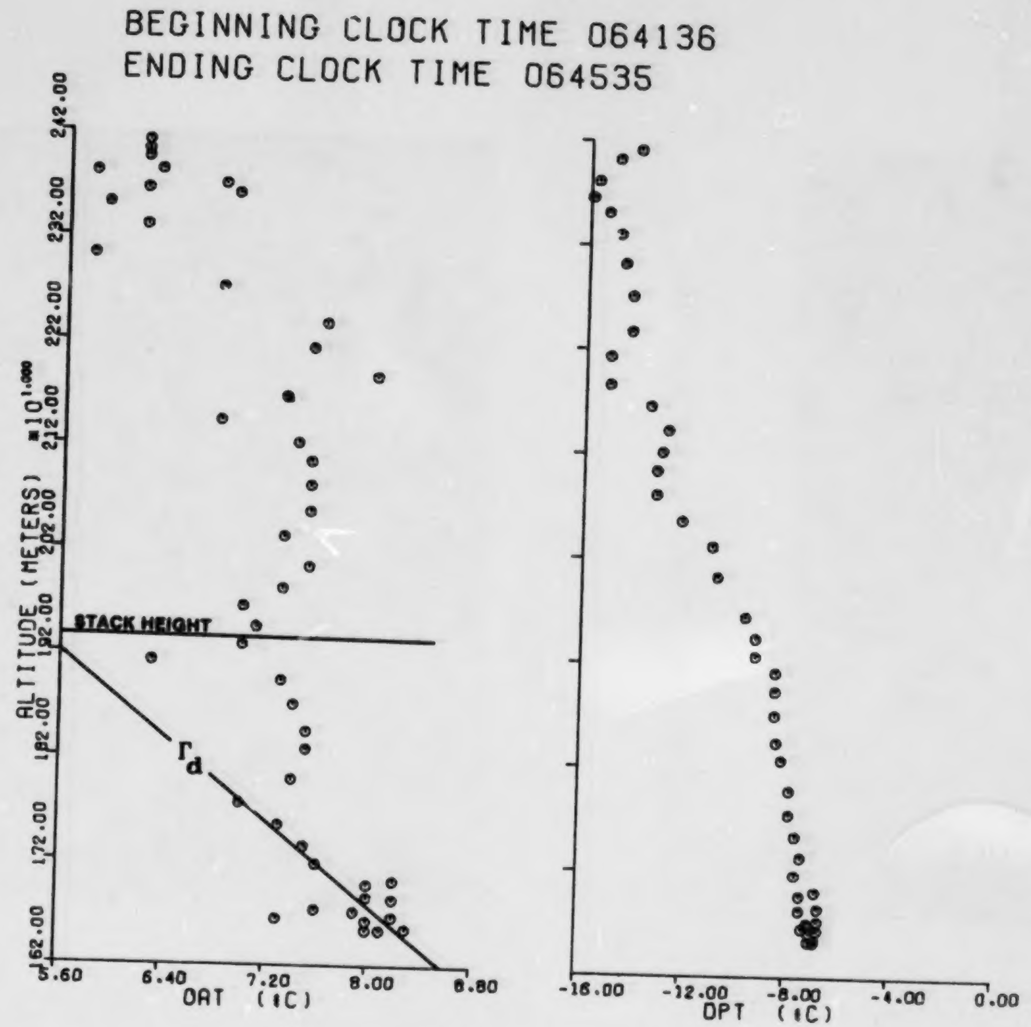

Figure A-58. Temperature and Dewpoint Soundings, 0641 MST, October 28, 1976.

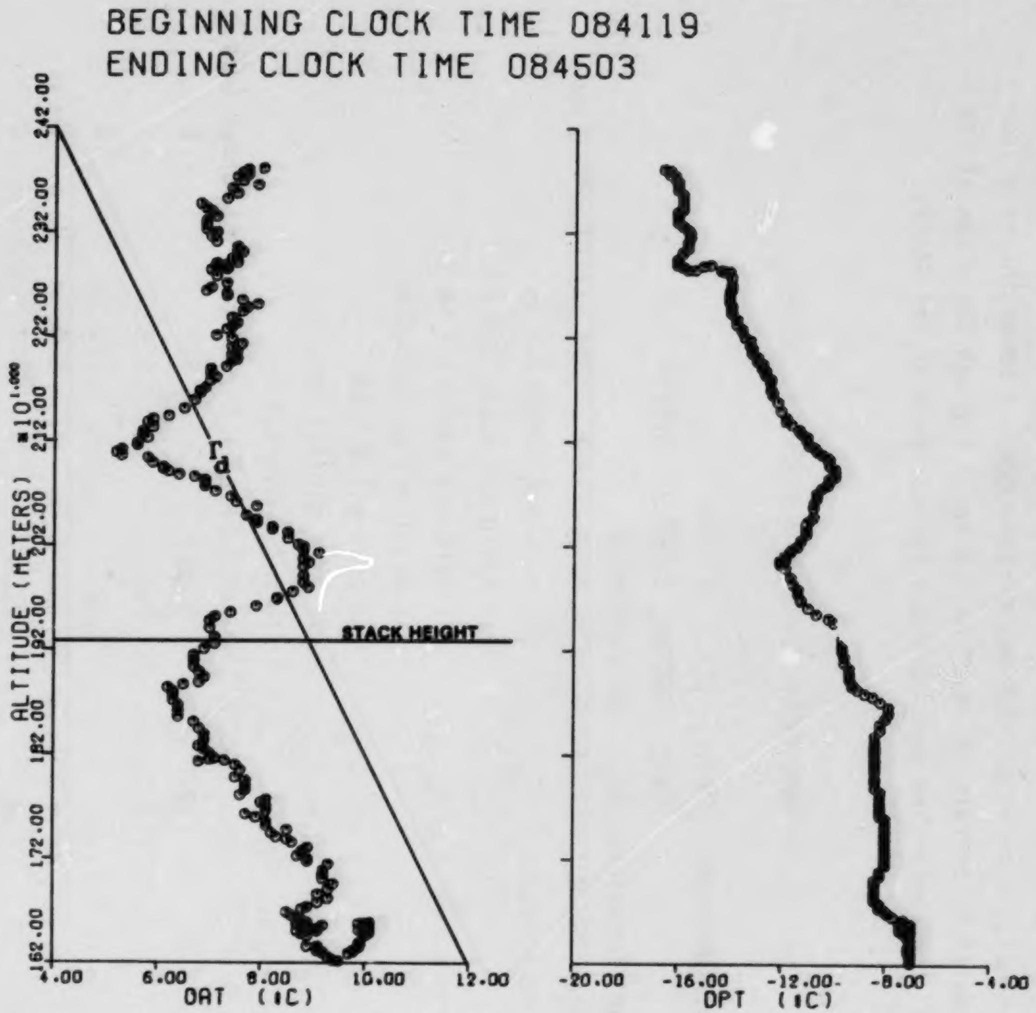

Figure A-59. Temperature and Dewpoint Soundings, 0841 MST, October 28, 1976.

October 29, 1976 0640-0827 MST

Early in the mission, stable conditions were observed below stack height and neutral conditions existed above (Figure A-62). By the end of the mission, neutral conditions existed above and below stack height. Only a thin stable layer remained, which was based at approximately 1700 m MSL (Figure A-63). A cross section was constructed 3.1 km southeast of the stack. Multiple spirals followed by transects through the plume at the height of the centerline were made 5.5 km southeast of the stack.

TABLE A-16
SUMMARY OF MISSION, OCTOBER 29, 1976

1. Butte Weather: 0551 CLR 210/04
   0850 70BRKN 200BRKN 320/04
2. Plant Emissions, SO_2: Not available
3. Centerline Height/ Distance/ Concentration: 2225 m/3.1 km/19.0 ppm
4. Three-minute σ_y, SO_2: 262 m/64 m/8 cases/3.1 km
   453 m/170 m/2 cases/5.5 km
   Three-minute σ_y, B_{scat}: 235 m/64 m/8 cases/3.1 km
   476 m/187 m/2 cases/5.5 km
5. σ_z, Cross Section, SO_2: 63 m/24 min/3.1 km
   σ_z, Cross Section, B_{scat}: 75 m/24 min/3.1 km
6. σ_z, Spiral, B_{scat}: 110 m/4.7 min/5.5 km
7. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0750	1950	257	1
0820	1950	256	1
	2220	276	10
0850	1950	260	1
	2220	277	4

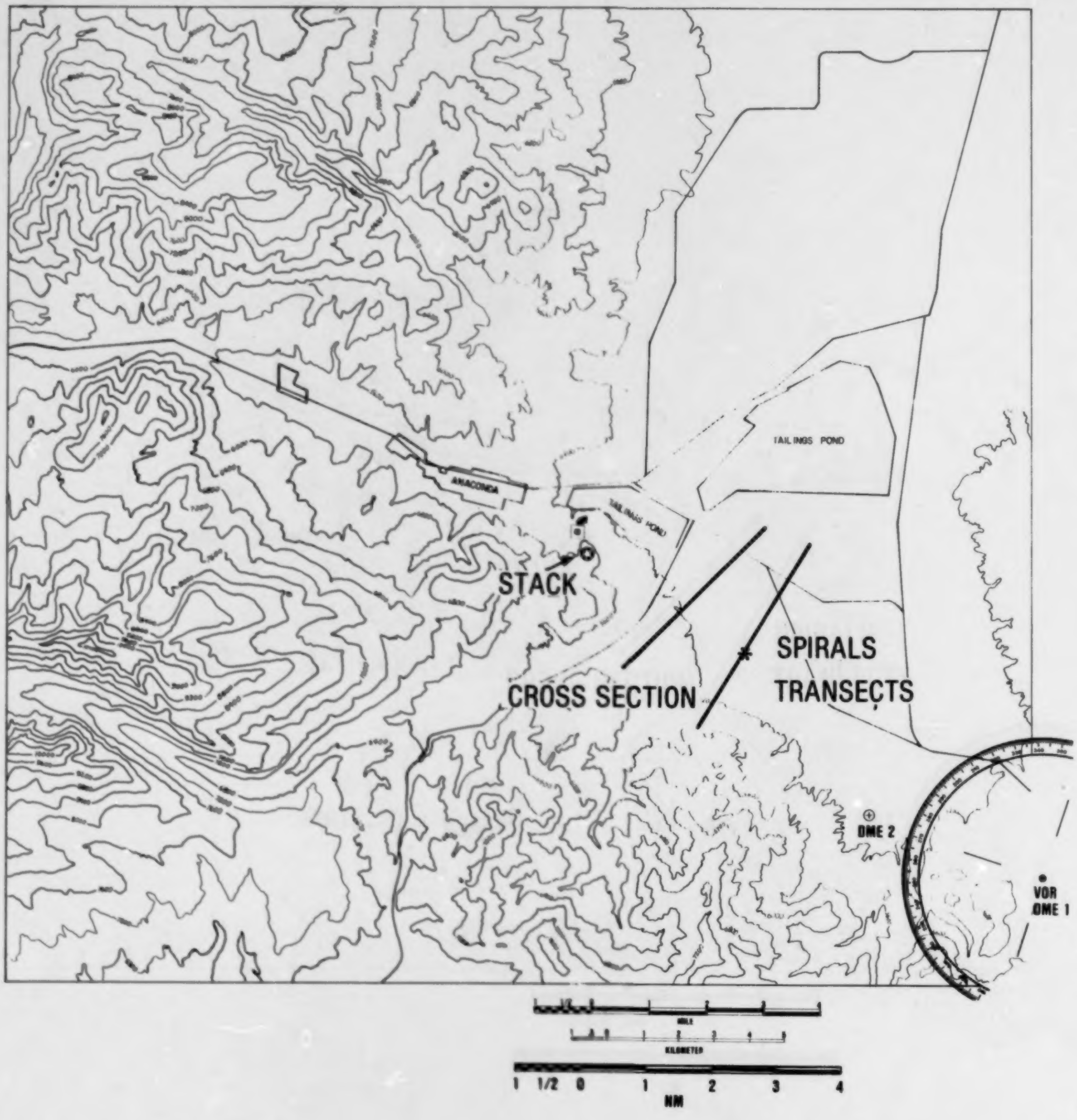

Figure A-60. Sampling Locations, October 29, 1976.

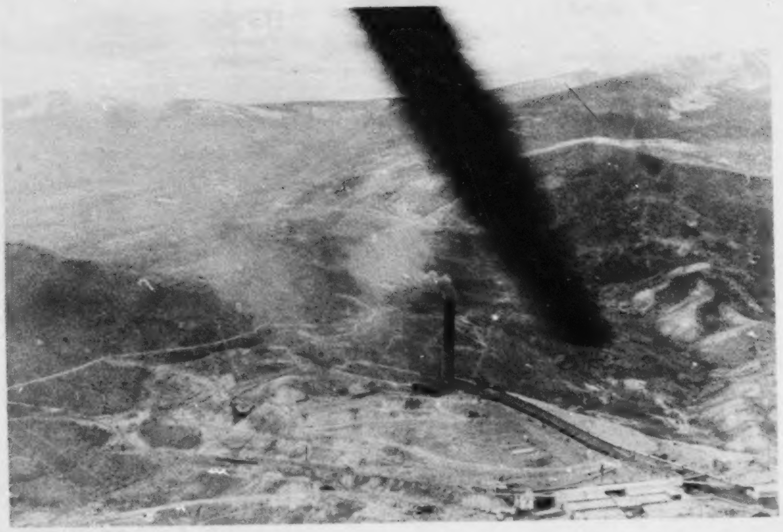

Figure A-61. Plume, October 29, 1976.

BEGINNING CLOCK TIME 064044
ENDING CLOCK TIME 064335

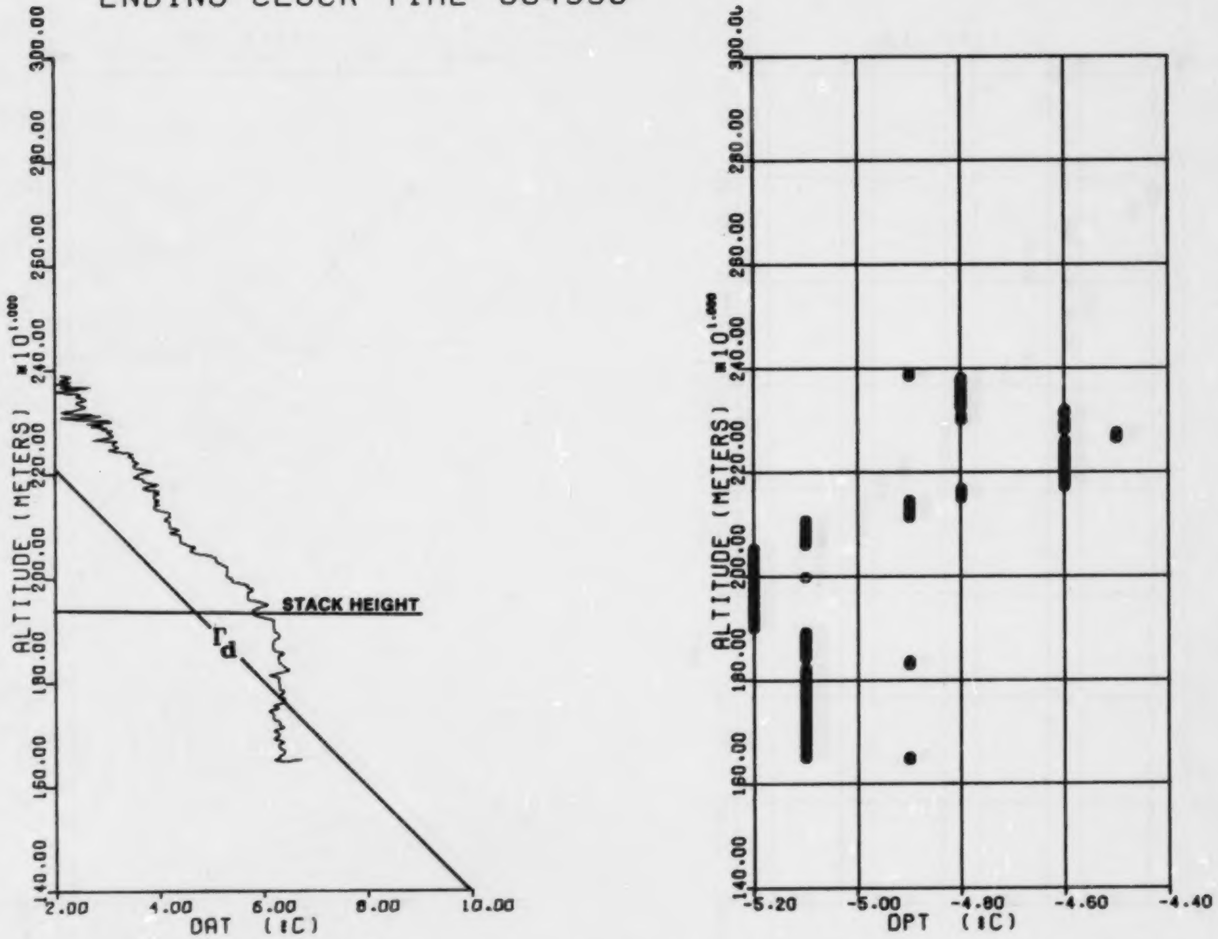

Figure A-62. Temperature and Dewpoint Soundings, 0640 MST, October 29, 1976.

BEGINNING CLOCK TIME 082326
ENDING CLOCK TIME 082729

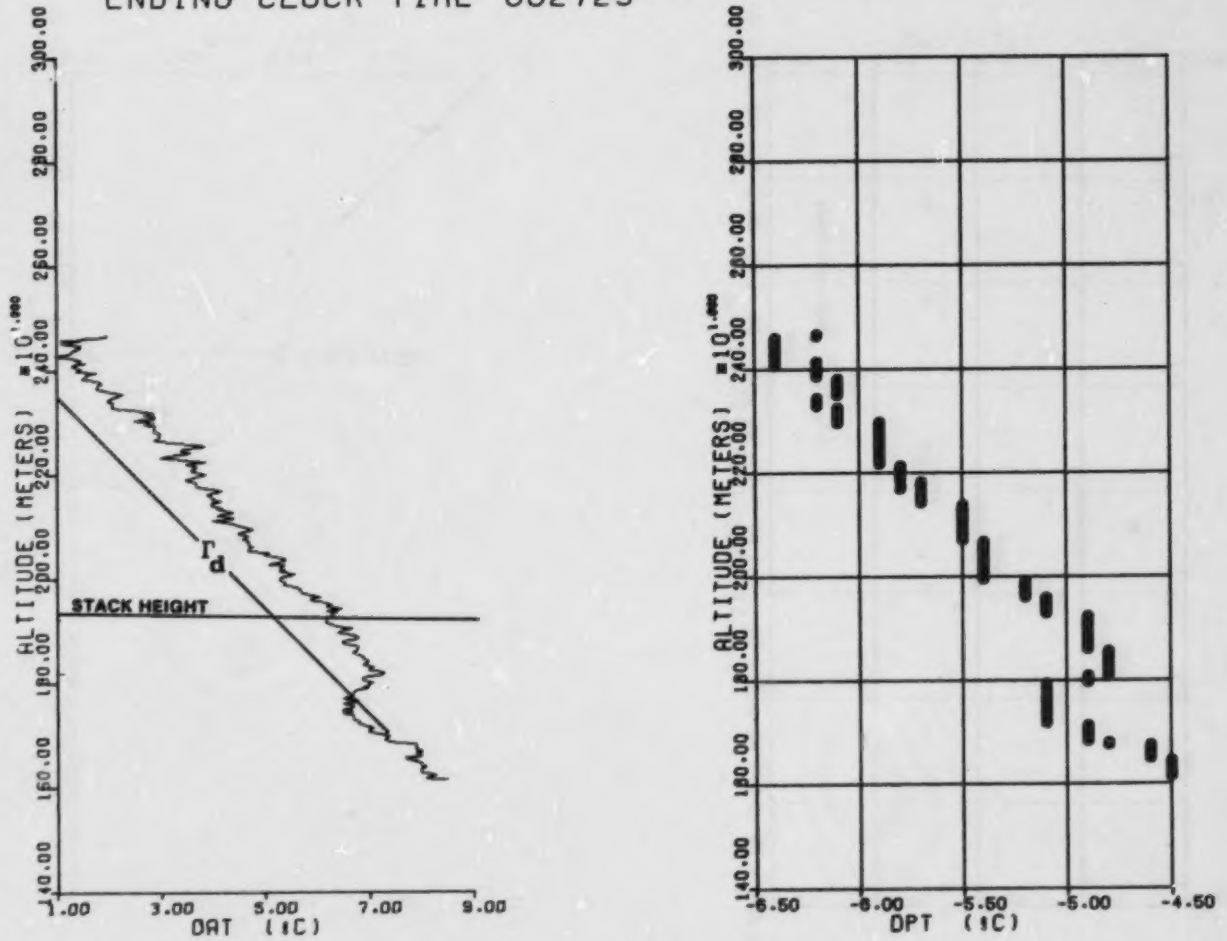

Figure A-63. Temperature and Dewpoint Soundings, 0823 MST, October 29, 1976.

November 1, 1976 0652-0759 MST

At the start of the sampling period, near neutral conditions below stack height coupled with stable conditions above (Figure A-67) produced fumigation conditions (Figure A-65). At approximately 0720 MST, a wind shift occurred and fumigation was no longer observed. A partial cross section was constructed 2.0 km northeast of the stack and another was attempted 2.0 km southeast of the stack. High winds, moderate turbulence and a shifting plume made sampling difficult during the latter part of the mission.

TABLE A-17
SUMMARY OF MISSION, NOVEMBER 1, 1976

1. Butte Weather: 0653 50BRKN 150BRKN 210/11
   0850 40BRKN 100 OVC 320/10
2. Plant Emissions, SO_2: 0630-0730 11.5 X 10^9 µg/s
   0730-0830 13.4 X 10^9 µg/s
3. Centerline Height/ Distance/ Concentration: 2140 m/2.0 km/16.1 ppm
4. Three-minute σ_y, SO_2: 222 m/91 m/12 cases/2.0 km
5. Three-minute σ_y, B_{scat}: 222 m/55 m/11 cases/2.0 km
6. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (^{o})	Speed (m/s)
0727	1770	269	5
	1950	268	7
	2130	272	2
0800	1770	349	3
	1950	315	6
	2130	307	13

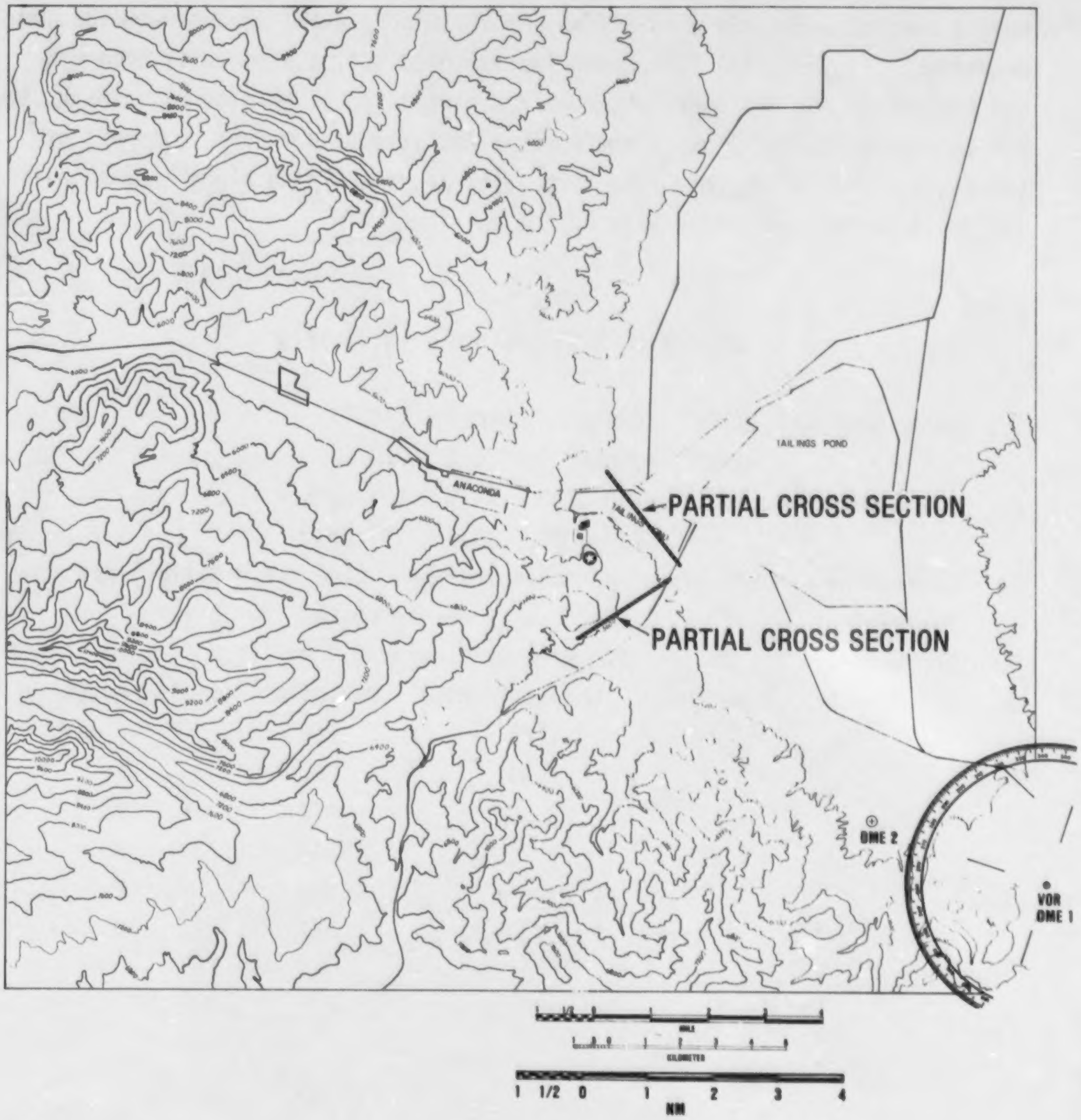

Figure A-64. Sampling Locations, November 1, 1976.

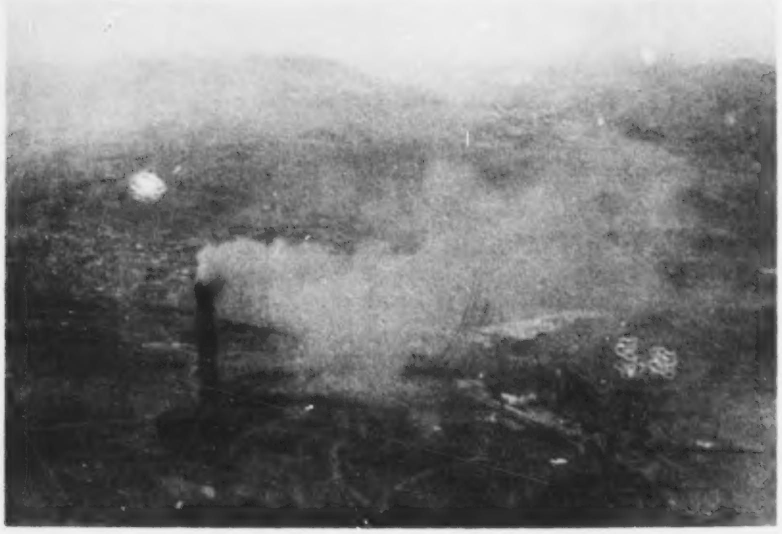

Figure A-65. Plume Under Fumigation Conditions, November 1, 1976.

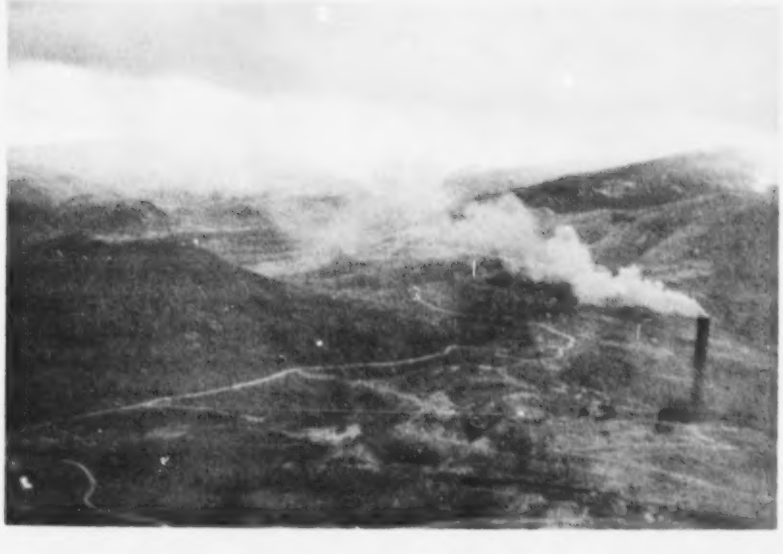

Figure A-66. Plume, November 1, 1976.

BEGINNING CLOCK TIME 065155
ENDING CLOCK TIME 065438

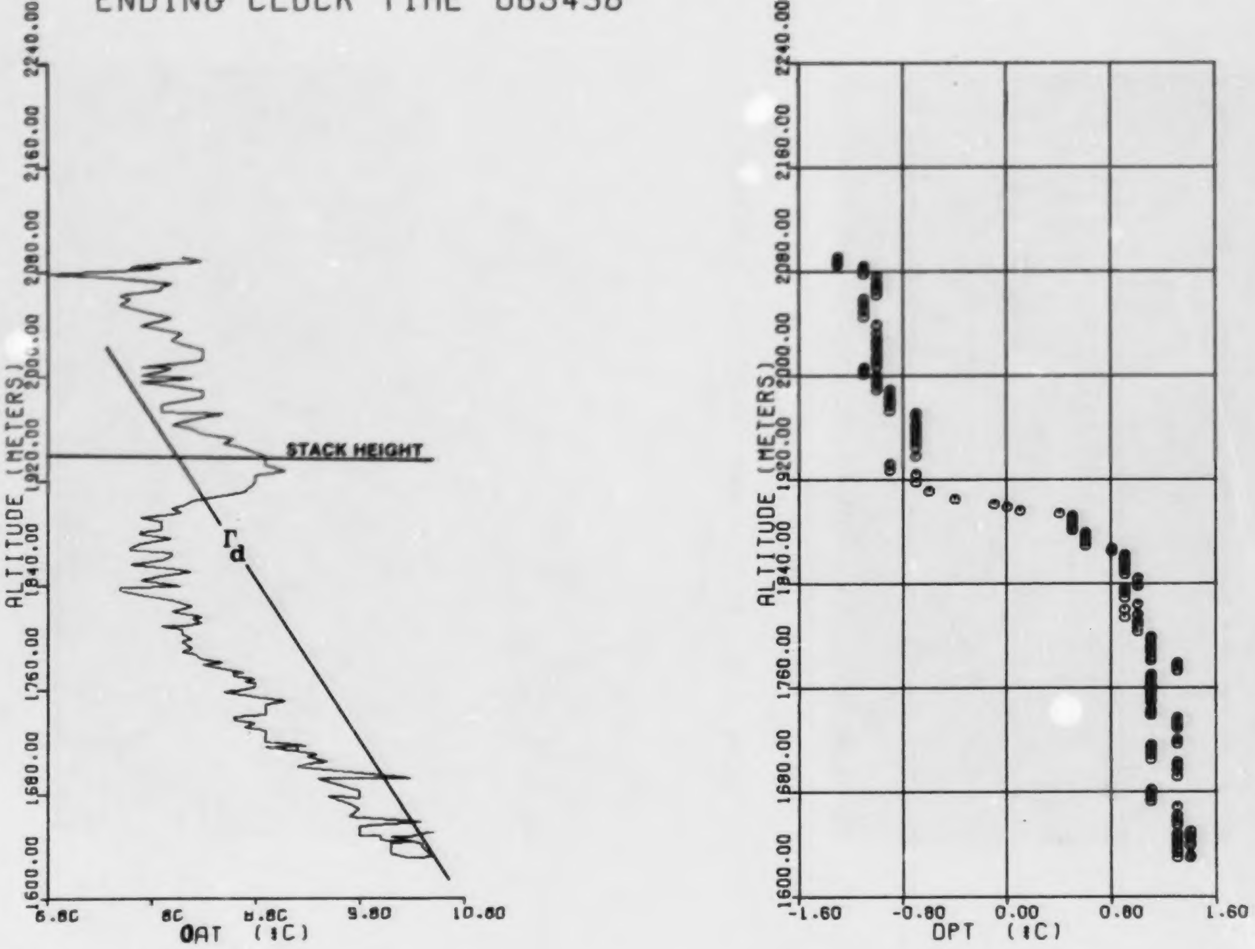

Figure A-67. Temperature and Dewpoint Soundings, 0651 MST, November 1, 1976.

BEGINNING CLOCK TIME 075703
ENDING CLOCK TIME 075859

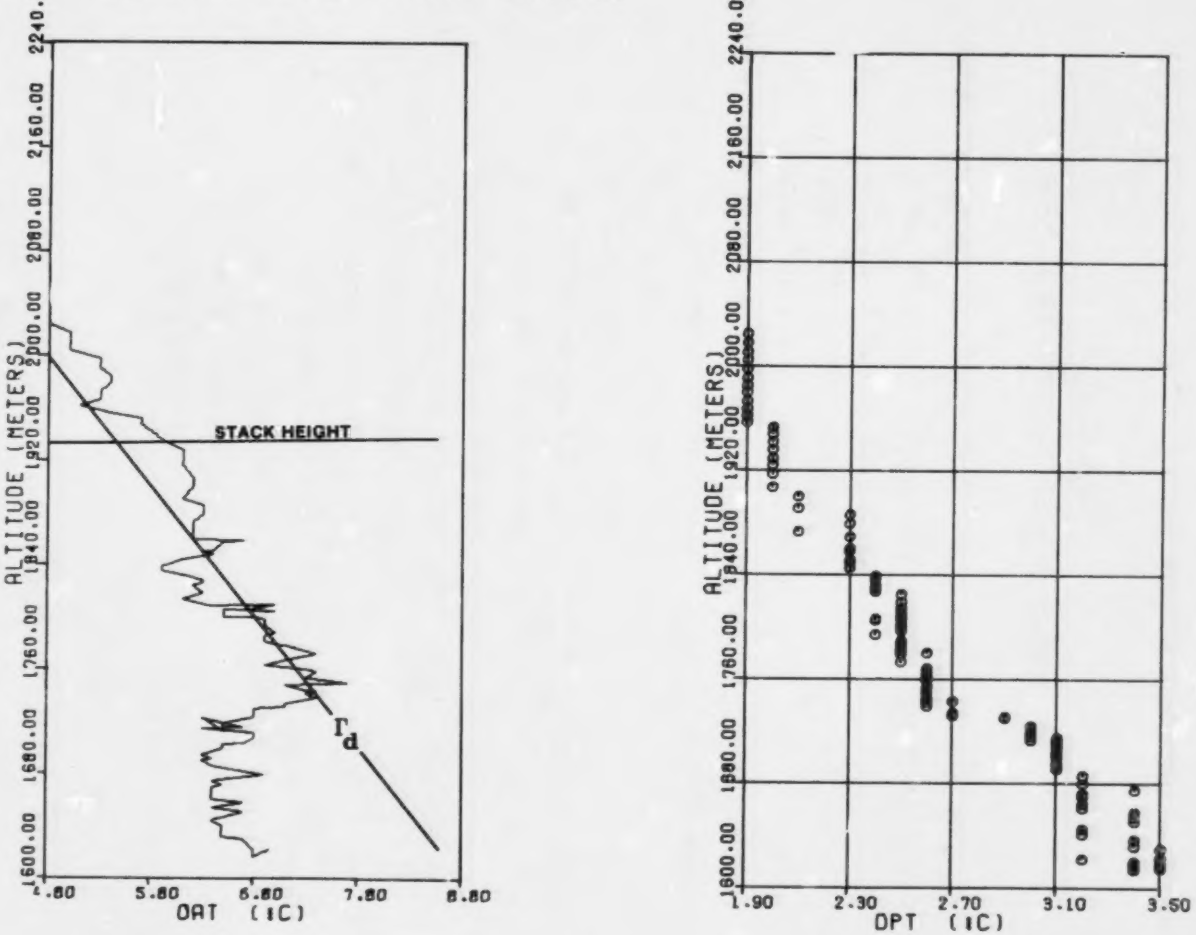

Figure A-68. Temperature and Dewpoint Soundings, 0757 MST, November 1, 1976.

November 3, 1976 0645-0842 MST

Neutral conditions above stack height and stable conditions below (Figure A-71 and A-72) produced a lofted plume throughout the mission (Figure A-70). Cross sections were developed at 1.0, 1.8, and 2.4 km southeast of the stack (Figure A-69).

TABLE A-18
SUMMARY OF MISSION, NOVEMBER 3, 1976

1. Butte Weather: 0950 20 SCT 50 SCT 200BRKN 330/04
2. Plant Emissions, SO_2: 0530-0630 10.4×10^9 μg/s
   0630-0730 9.9×10^9 μg/s
   0730-0830 13.9×10^9 μg/s
   0830-0930 12.1×10^9 μg/s
3. Centerline Height/ Distance/ Concentrations: 2286 m/1.0 km/25.5 ppm.
4. Three-minute σ_y, SO_2: 147 m/34 m/7 cases/1.0 km
   204 m/60 m/10 cases/1.6 km
   238 m/90 m/12 cases/3.0 km
   Three-minute σ_y, B_{scat}: 150 m/34 m/7 cases/1.0 km
   204 m/60 m/10 cases/1.6 km
   238 m/90 m/12 cases/3.0 km
   Three-minute σ_y, B_{scat}: 150 m/34 m/8 cases/1.0 km
   231 m/99 m/11 cases/1.6 km
   243 m/111 m/11 cases/3.0 km
5. σ_z, Cross Section, SO_2: 61 m/25 min/1.0 km
6. σ_z, Cross Section, B_{scat}: 80 m/55 min/ 1.0 km
   81 m/55 min/1.6 km
   92 m/33 min/3.0 km

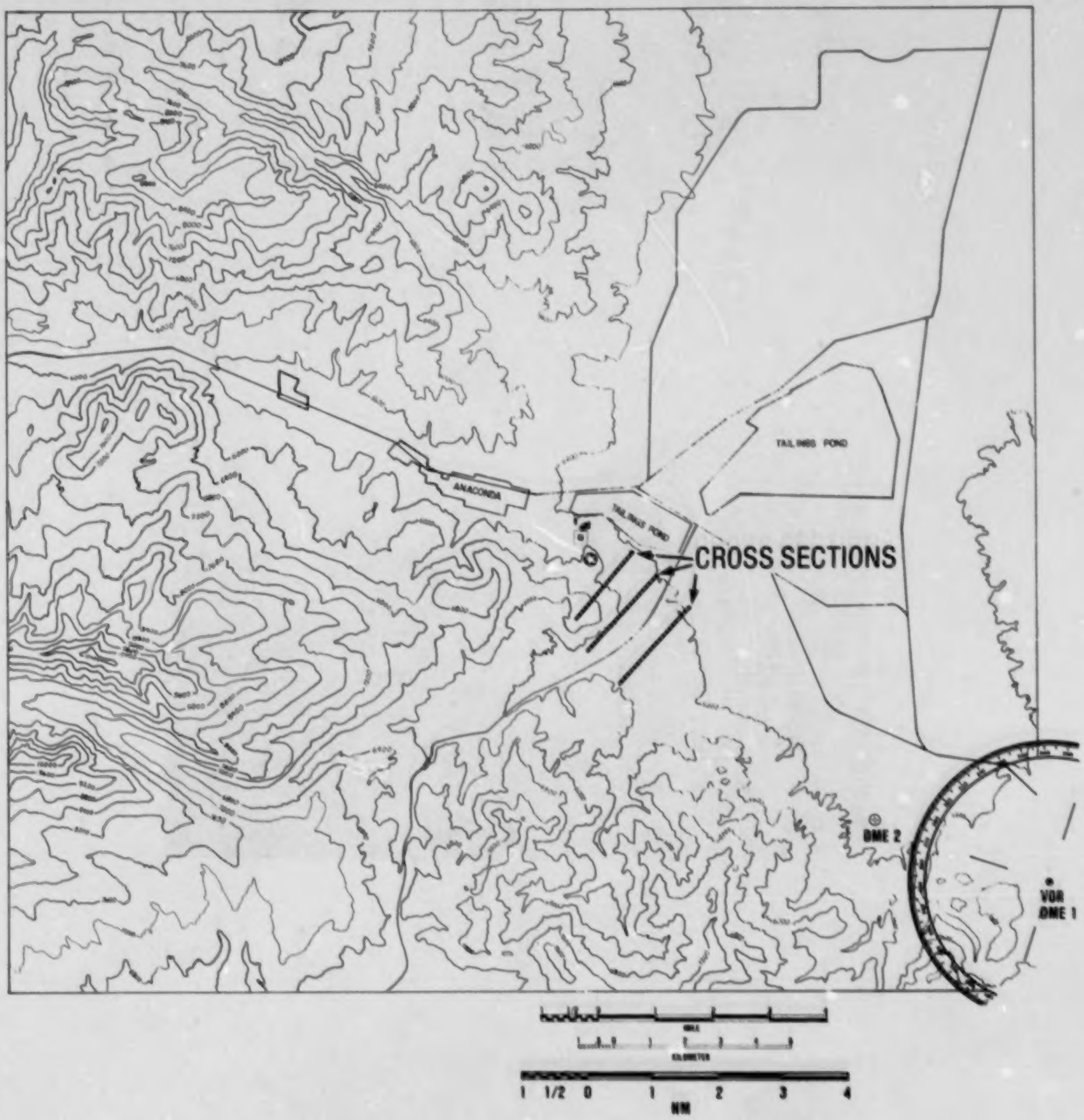

Figure A-69. Sampling Locations, November 3, 1976.

7. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0655	1950	235	5
	2280	302	6
0725	1950	240	3
0825	1950	226	6
	2280	297	5
0855	1950	226	4
	2280	300	4

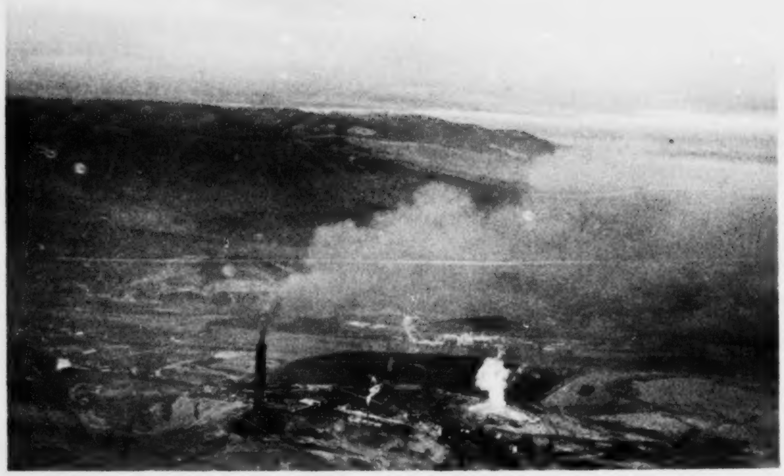

Figure A-70. Plume, November 3, 1976.

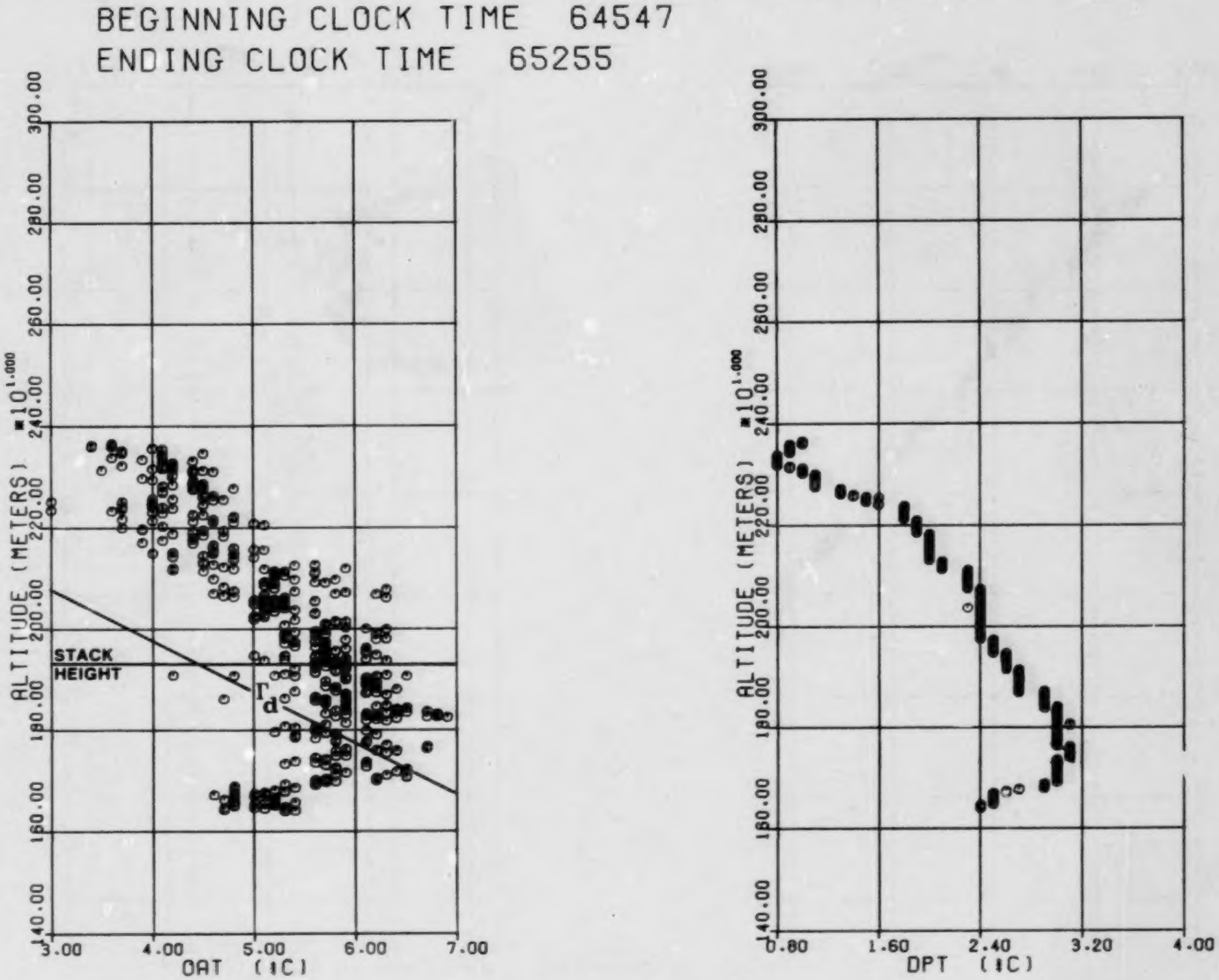

Figure A-71. Temperature and Dewpoint Soundings, 0645 MST, November 3, 1976.

BEGINNING CLOCK TIME 083818
ENDING CLOCK TIME 084223

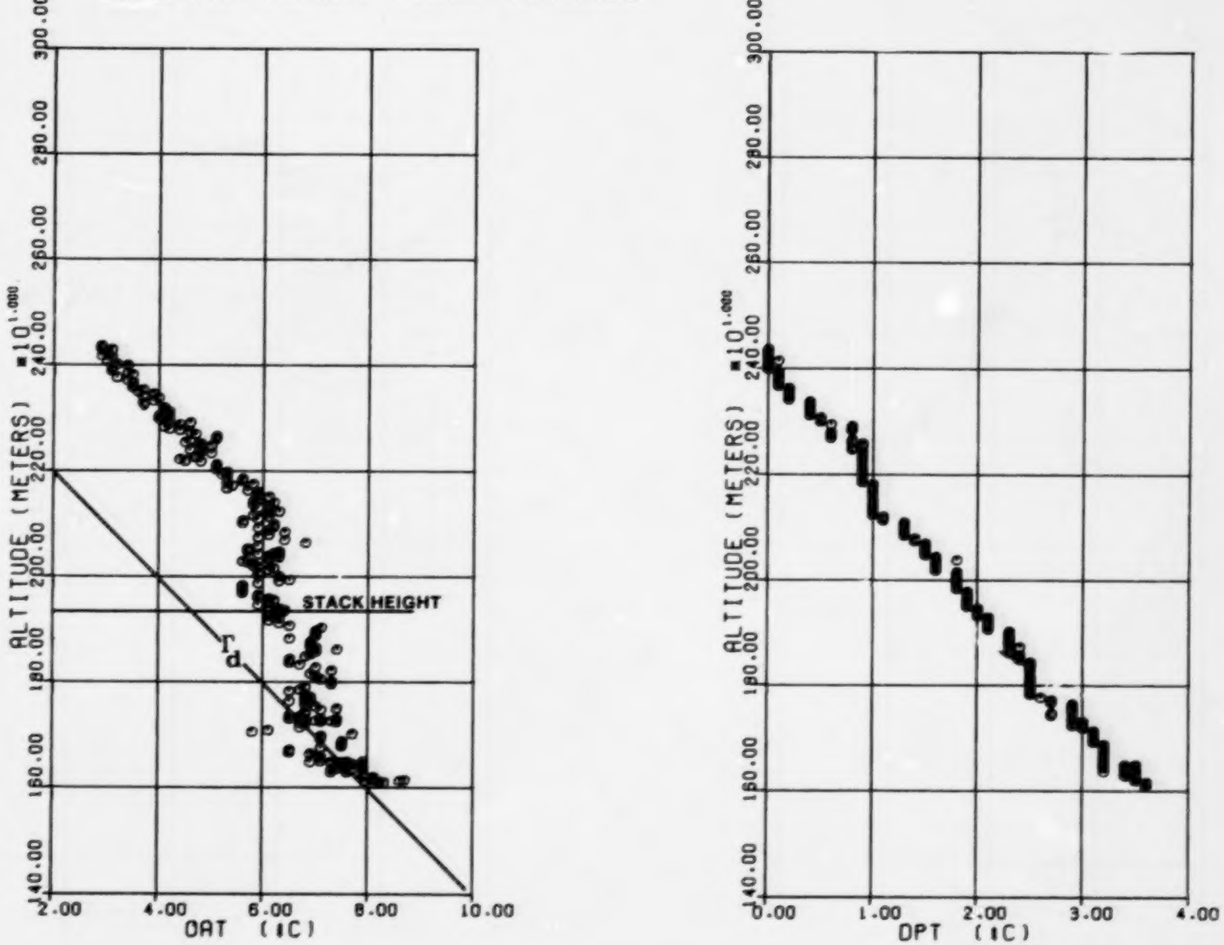

Figure A-72. Temperature and Dewpoint Soundings, 0838 MST, November 3, 1976.

November 4, 1976 1040-1325 MST

Stable conditions were noted throughout the sampling period (Figure A-75 and A-76). A cross section was developed 1.6 km southeast of the stack. Multiple spirals followed by traverses at centerline height were made 5.0 km southeast of the stack (Figure A-73). Table A-19 summarizes the results of the flight.

TABLE A-19
SUMMARY OF MISSION, NOVEMBER 4, 1976

1. Butte Weather: 0950 100 BRKN CLM
    1355 80 BRKN 200 OVC 170/04
2. Plant Emission, SO_2: 0930-1030 12.8 X 10^9 μg/s
    1030-1130 12.0 X 10^9 μg/s
    1130-1230 14.0 X 10^9 μg/s
    1230-1330 13.1 X 10^9 μg/s
3. Centerline Height/Distance/Concentrations: 2347 m/1.6 km/11.1 ppm
4. Three-minute σ_y, SO_2: 259 m/63 m/13 cases/1.6 km
    249 m/44 m/9 cases/5.0 km
    Three-minute σ_y, B_{scat}: 291 m/78 m/15 cases/1.6 km
    267 m/47 m/10 cases/5.0 km
5. σ_z, Cross Section, SO_2: 107 m/40 min/1.6 km
    σ_z, Cross Section, B_{scat}: 113 m/40 min/1.6 km
6. σ_z, Spiral, SO_2: 53 m/1.6 min/5.0 km
    σ_z, Spiral, SO_2: 86 m/2.7 min/5.0 km
    σ_z, Spiral, SO_2: 59 m/2.5 min/5.0 km
    σ_z, Spiral, SO_2: 90 m/2.2 min/5.0 km
    σ_z, Spiral, SO_2: 48 m/2.3 min/5.0 km
    σ_z, Spiral, B_{scat}: 60 m/2.5 min/5.0 km
    σ_z, Spiral, B_{scat}: 65 m/2.4 min/5.0 km
    σ_z, Spiral, B_{scat}: 86 m/2.7 min/5.0 km
    σ_z, Spiral, B_{scat}: 60 m/2.5 min/5.0 km
    σ_z, Spiral, B_{scat}: 84 m/2.2 min/5.0 km

7. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0930	1950	217	5
	2340	288	12
1000	1950	217	8
	2340	281	12
1030	1950	211	9
	2340	276	16
1100	1950	210	6
	2340	293	8
1130	1950	223	7
	2340	285	10
1200	1950	219	4
1230	1950	265	3
	2340	288	9
1300	1950	301	3
	2340	300	9

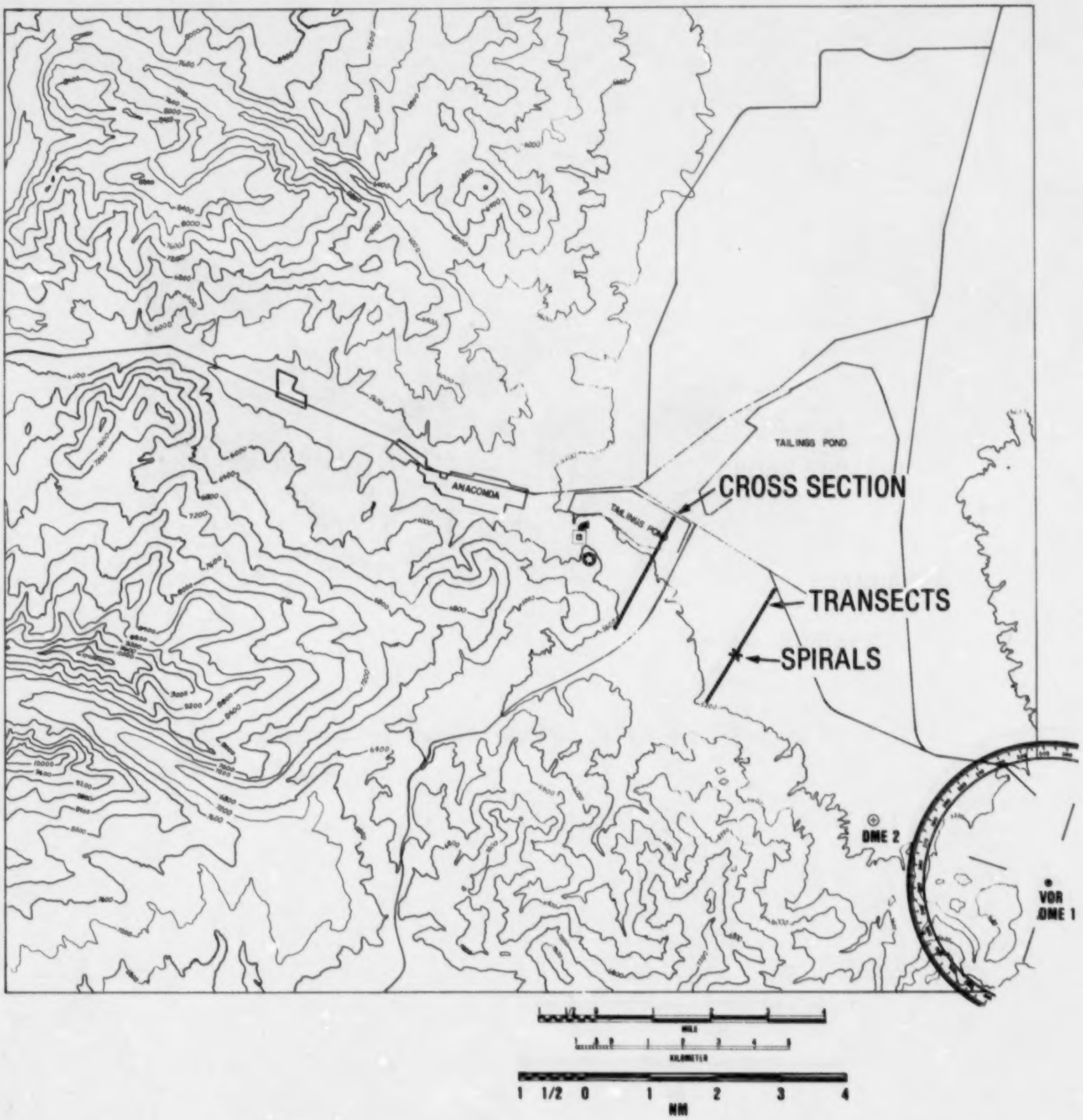

Figure A-73. Sampling Locations, November 4, 1976.

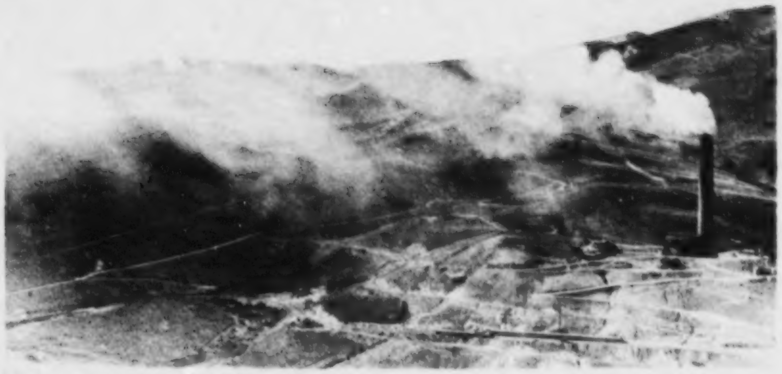

Figure A-74. Plume, November 4, 1976.

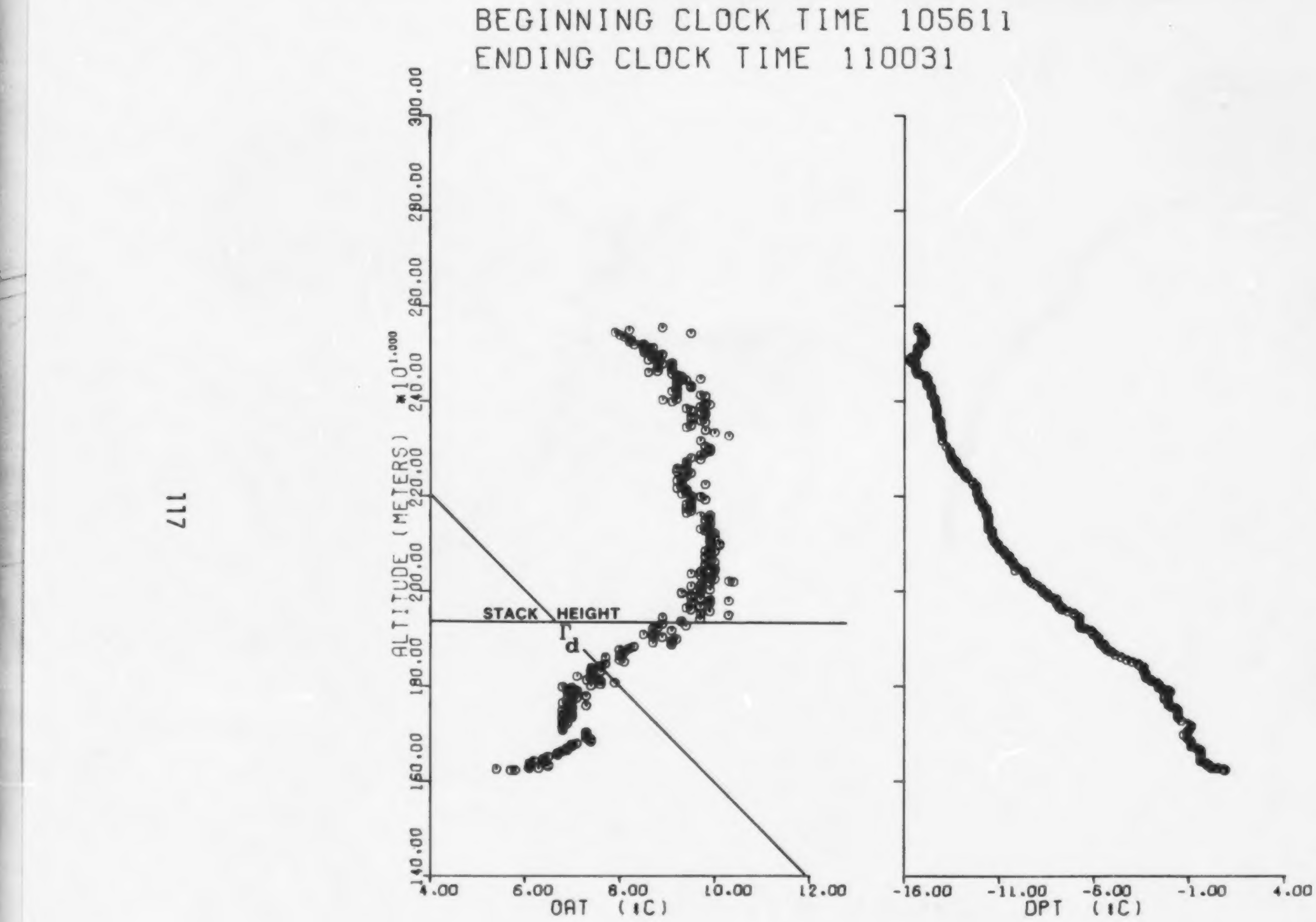

Figure A-75. Temperature and Dewpoint Soundings, 1056 MST, November 4, 1976.

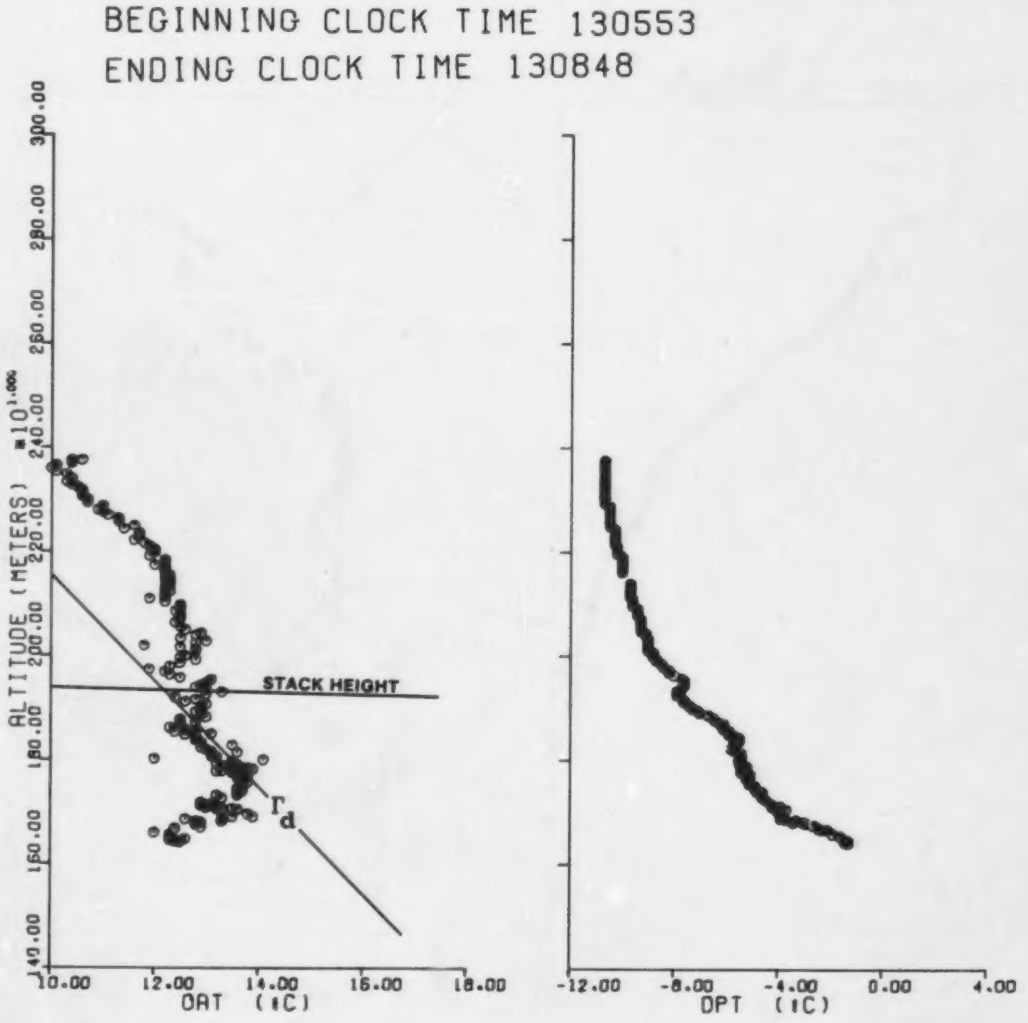

Figure A-76. Temperature and Dewpoint Soundings, 1305 MST, November 4, 1976.

November 5, 1976 1230-1312 MST

Neutral atmospheric conditions were initially observed. These were replaced by near-isothermal conditions as katabatic flow produced downwash conditions (Figures A-78 and A-79). The portable SO_2 monitor was placed 2.9 km northeast of the stack (Figure A-77). Two cross sections were developed in this area.

TABLE A-20
SUMMARY OF MISSION, NOVEMBER 5, 1976

1. Butte Weather: 0950 120 SCT HI OVC CLM
   1350 120 SCT HI OVC CLM
2. Plant Emissions, SO_2: 1130-1230 12.9×10^9 μg/s
   1230-1330 13.4×10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 1805 m/2.9 km/10.5 ppm
4. Three-minute σ_y, SO_2: 279 m/132 m/12 cases/2.9 km
5. Three-minute σ_y, B_{scat}: 241 m/86 m/8 cases/2.9 km
6. σ_z, Cross Section, SO_2: 95 m/61 min/2.9 km
7. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (^{o})	Speed (m/s)
1130	1950	234	5
1200	1950	267	6
1230	1950	305	6
1300	1950	285	9

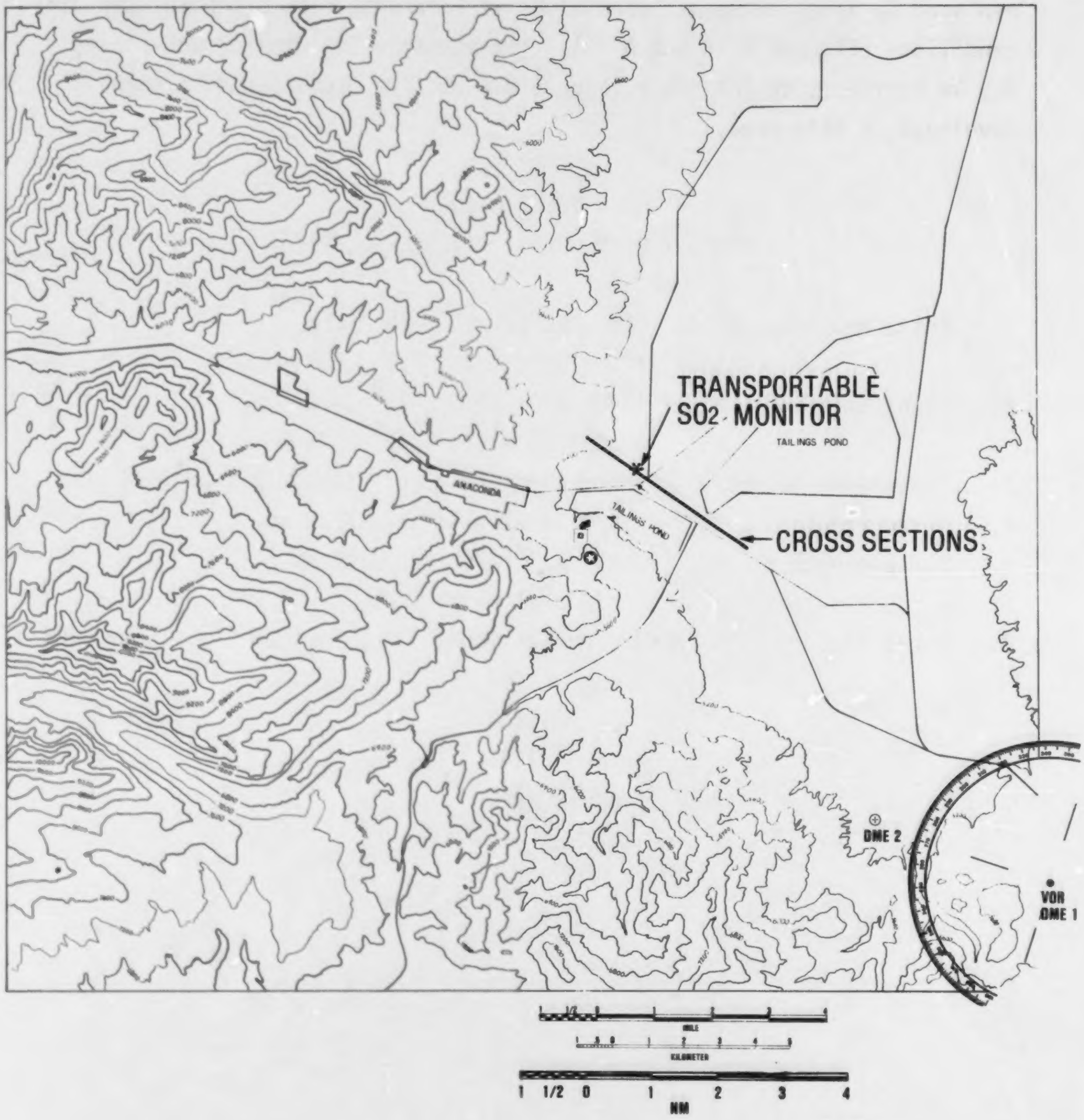

Figure A-77. Sampling Locations, November 5, 1976.

Figure A-78. Plume, November 5, 1976.

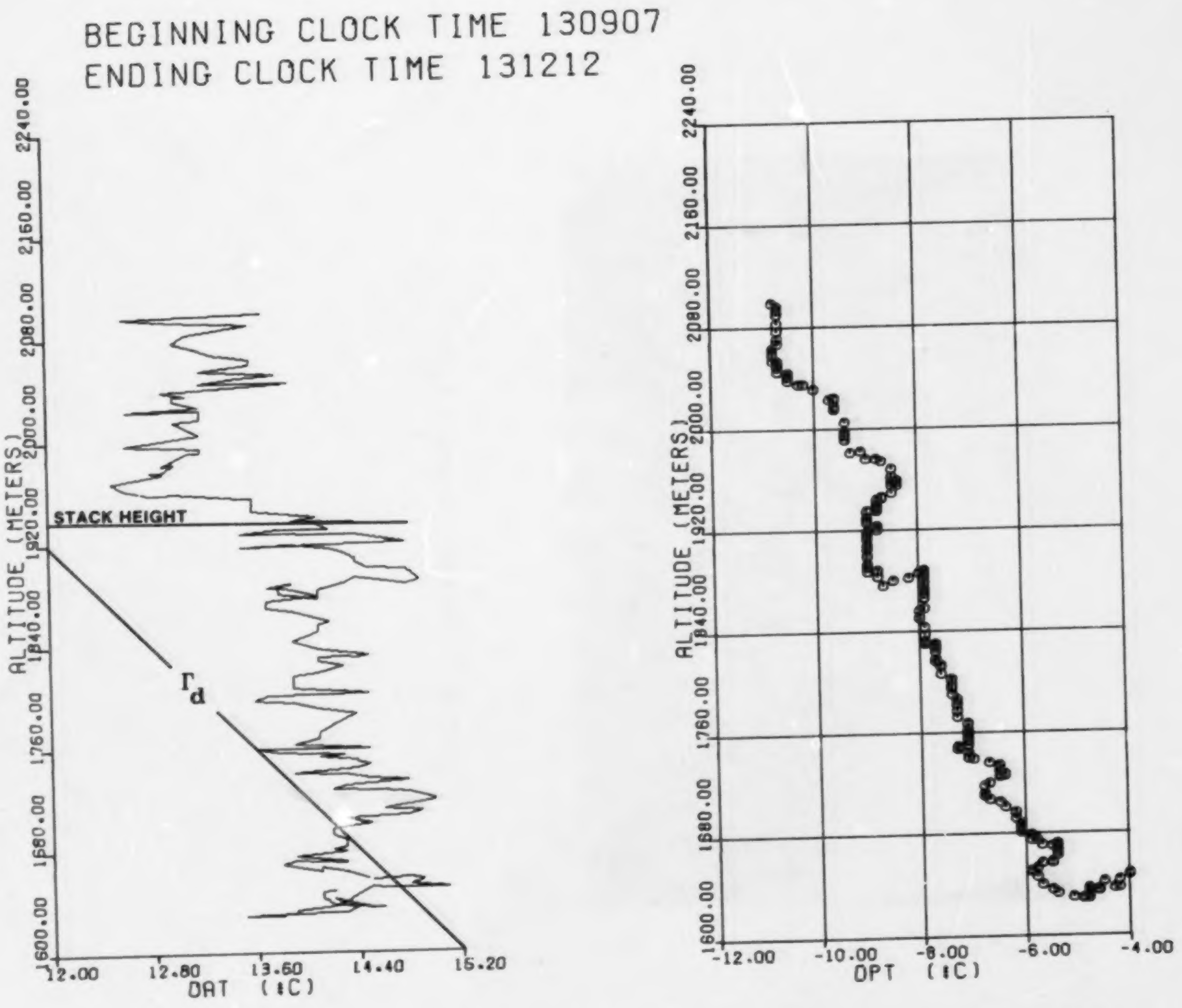

Figure A-79. Temperature and Dewpoint Soundings, 1309 MST, November 5, 1976.

November 8, 1976 1230-1350 MST

Neutral conditions were observed during the mission. Cross sections were developed 0.8 km northeast and 1.7 km southeast of the stack.

TABLE A-21
SUMMARY OF MISSION, NOVEMBER 8, 1976

1. Butte Weather: 55 BRKN 120 BRKN 340/05
2. Plant Emissions, SO_2: 1030-1130 6.7×10^9 μg/s
   1130-1230 10.8×10^9 μg/s
   1230-1330 8.1×10^9 μg/s
   1330-1430 6.0×10^9 μg/s
3. Centerline Height/ Direction/ Concentration: 2073 m/6.8 km/ 11.8 ppm
4. Three-minute σ_y, SO_2: 186 m/ 59 m/ 6 cases/ 0.8 km
   141 m/ 12 m/ 5 cases/ 1.7 km
   Three-minute σ_y, B_{scat}: 189 m/ 70 m/ 6 cases/ 0.8 km
   131 m/ 22 m/ 5 cases/ 1.7 km
5. σ_z, Cross Section, SO_2: 67 m/ 20 min/ 0.8 km
   54 m/ 15 min/ 1.7 km
6. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (^{o})	Speed (m/s)
0930	1950	314	4
	2070	310	5
1000	1950	305	3
	2070	296	5
1030	1950	287	4
	2070	289	4
1100	1950	296	4
	2070	299	5
1130	1950	296	5
	2070	310	3
1200	1950	289	3
	2070	304	2

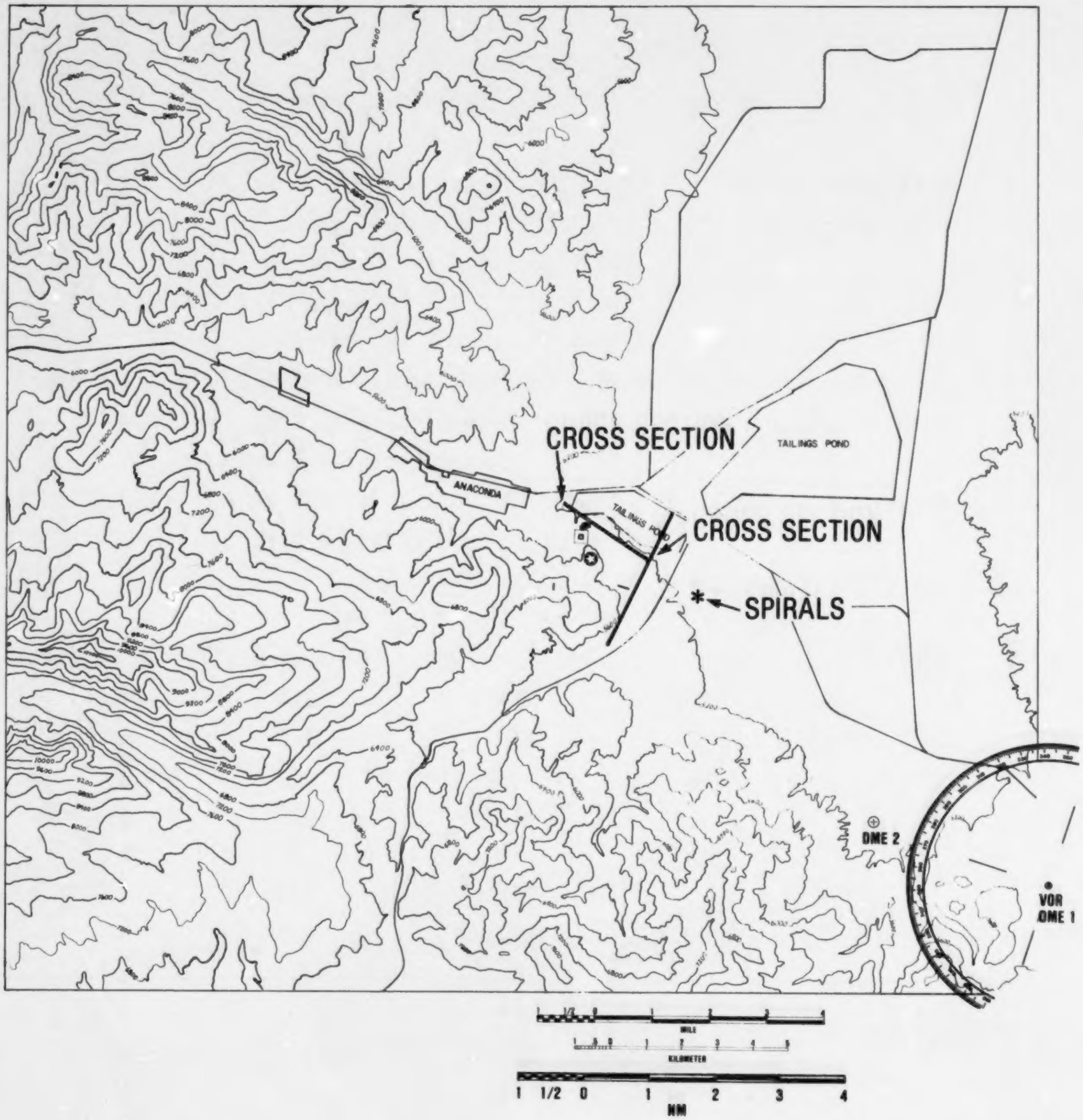

Figure A-80. Sampling Locations, November 8, 1976.

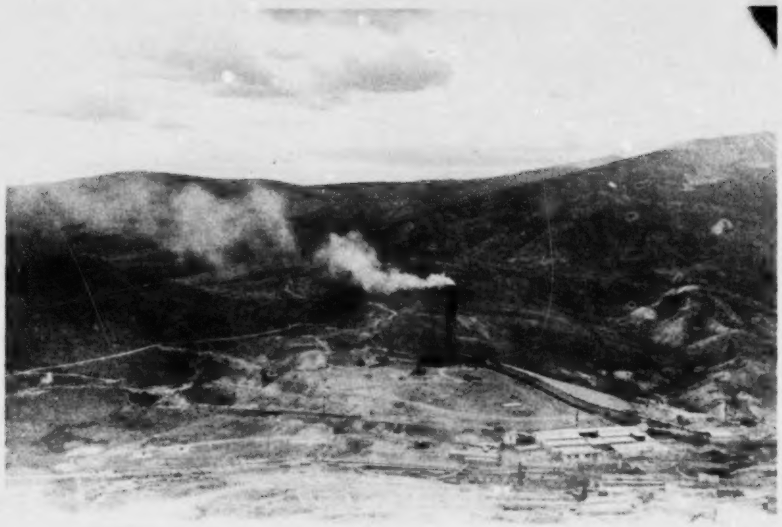

Figure A-81. Plume, November 8, 1976.

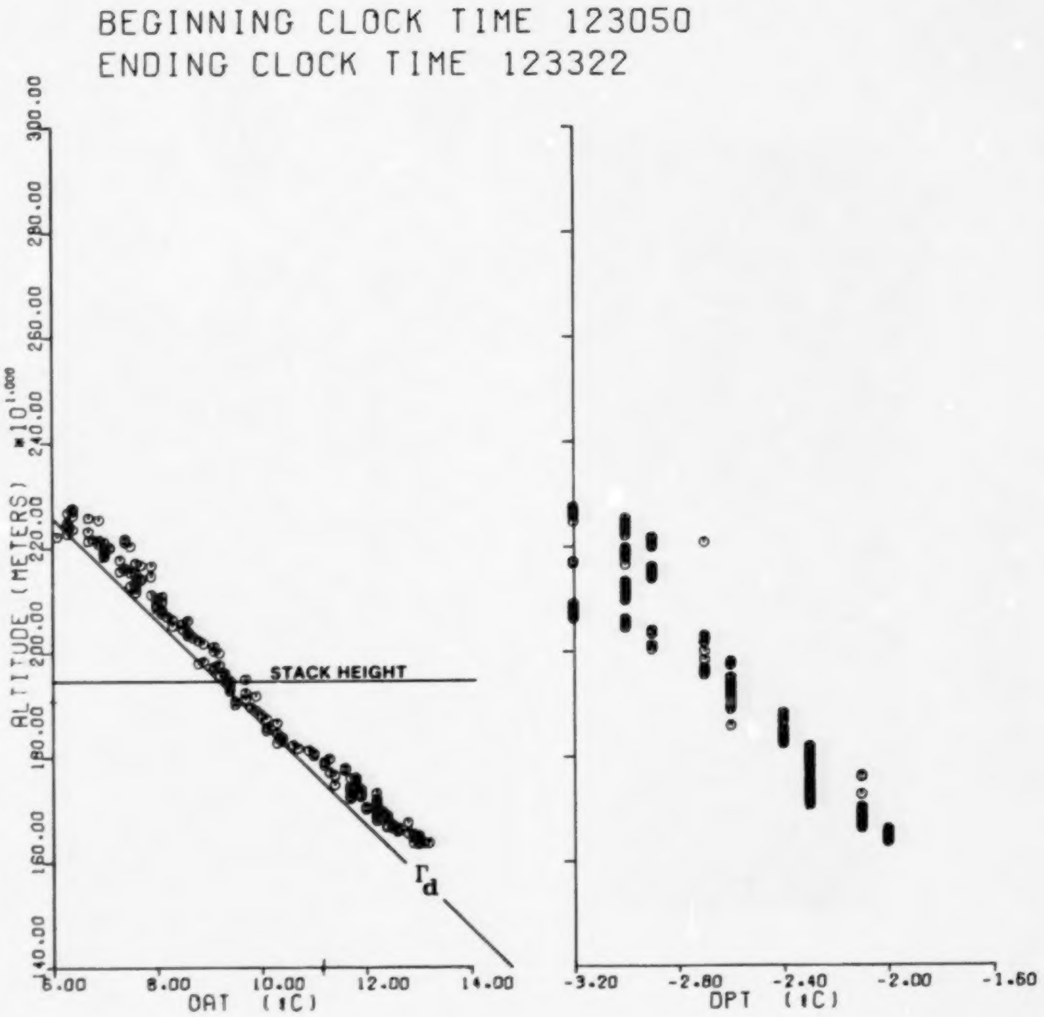

Figure A-82. Temperature and Dewpoint Soundings, 1230 MST, November 8, 1976.

November 9, 1976 1208-1310 MST

Neutral stability was observed throughout the mission (Figures A-85 and A-86). Cross sections were developed at 0.8 and 1.7 km. Low emissions and moderate winds made sampling difficult.

TABLE A-22
SUMMARY OF MISSION, NOVEMBER 9, 1976

1. Butte Weather: 1150 MST 30 SCT 200 THN BRKN 330/06
2. Plant Emissions, SO_2: 1030-1130 4.1×10^9 μg/s
   1130-1230 1.7×10^9 μg/s
   1230-1330 4.8×10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 1973 m/ 1.7 km/ 2.0 ppm
4. Three-minute σ_y, SO_2: 213 m/ 86 m/ 2 cases/ 0.8 km
   Three-minute σ_y, B_{scat}: 163 m/ 65 m/ 4 cases/ 0.8 km
5. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
1200	1950	230	2
	1980	238	2
1230	1950	265	4
	1980	269	4
1300	1950	207	1
	1980	227	1

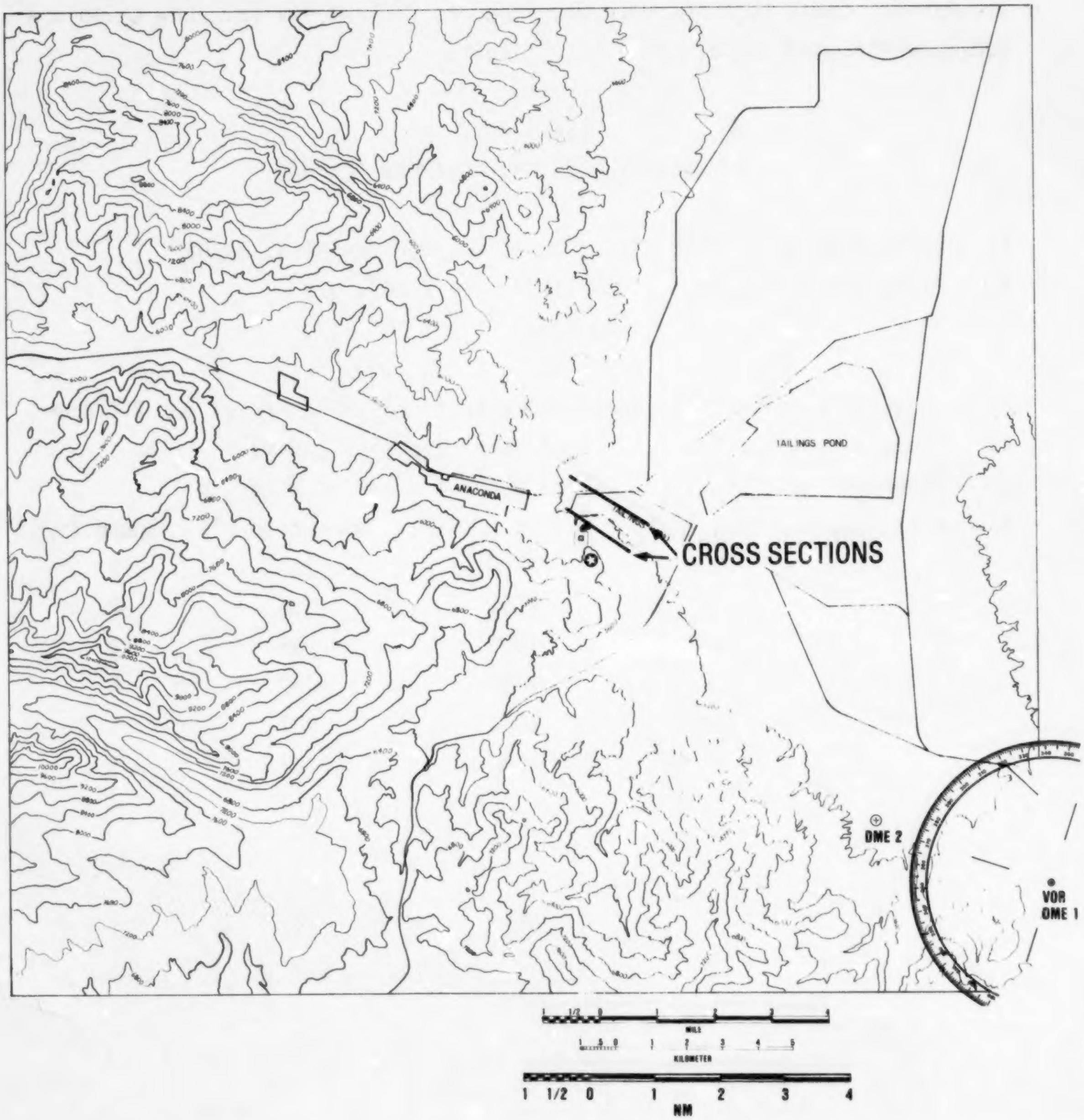

Figure A-83. Sampling Locations, November 9, 1976.

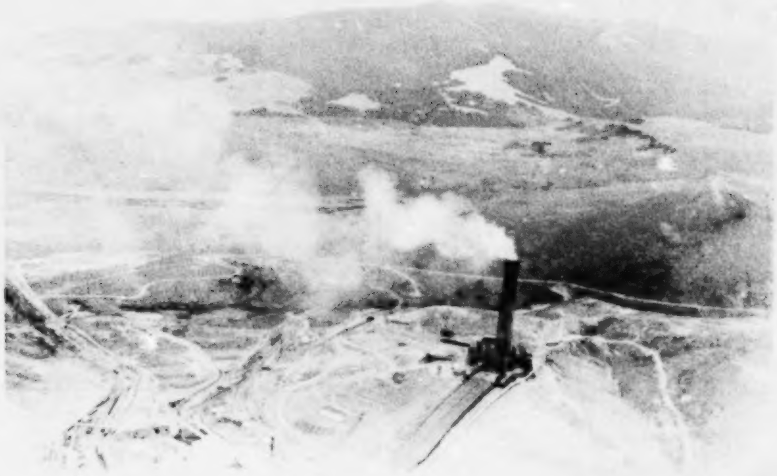

Figure A-84. Plume, November 9, 1976.

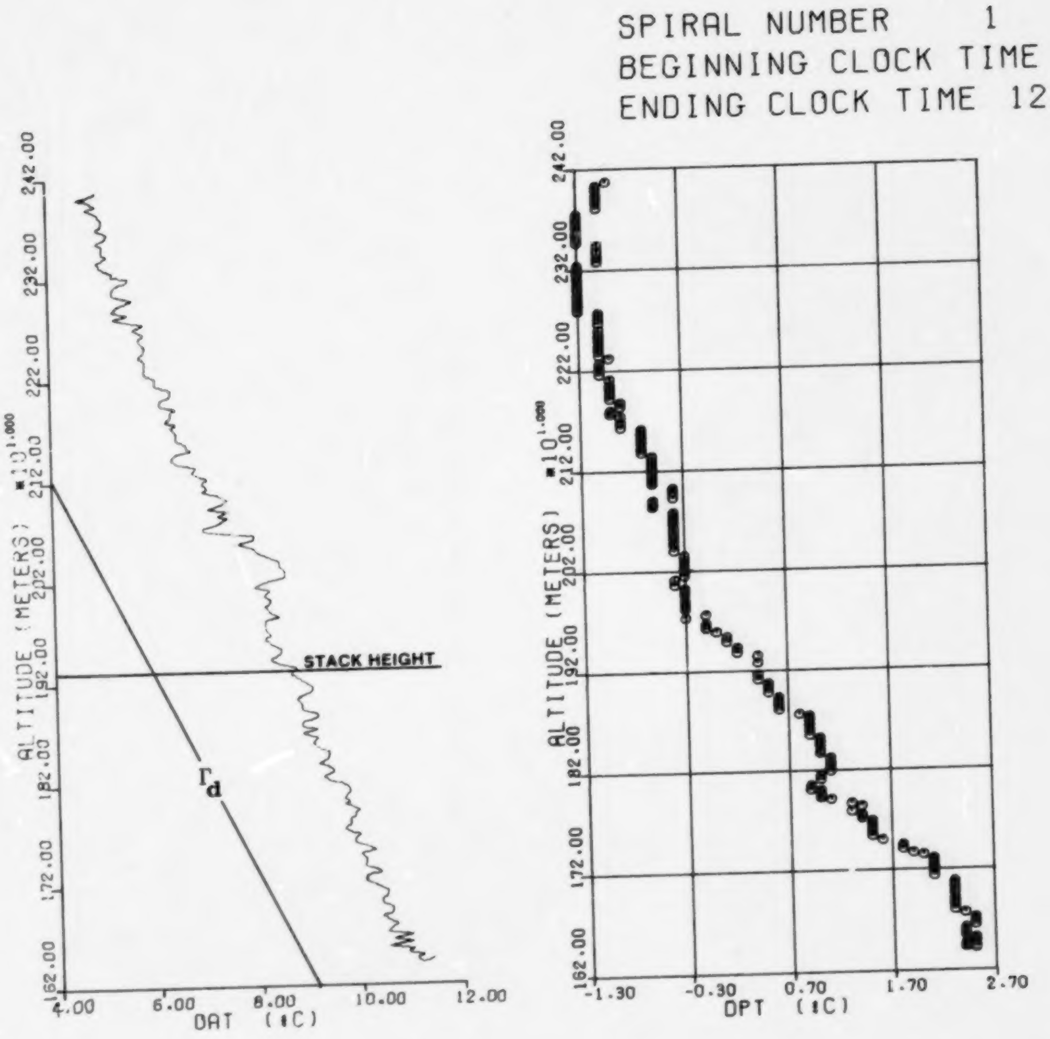

Figure A-85. Temperature and Dewpoint Soundings, 1208 MST, November 9, 1976.

BEGINNING CLOCK TIME 130756
ENDING CLOCK TIME 131006

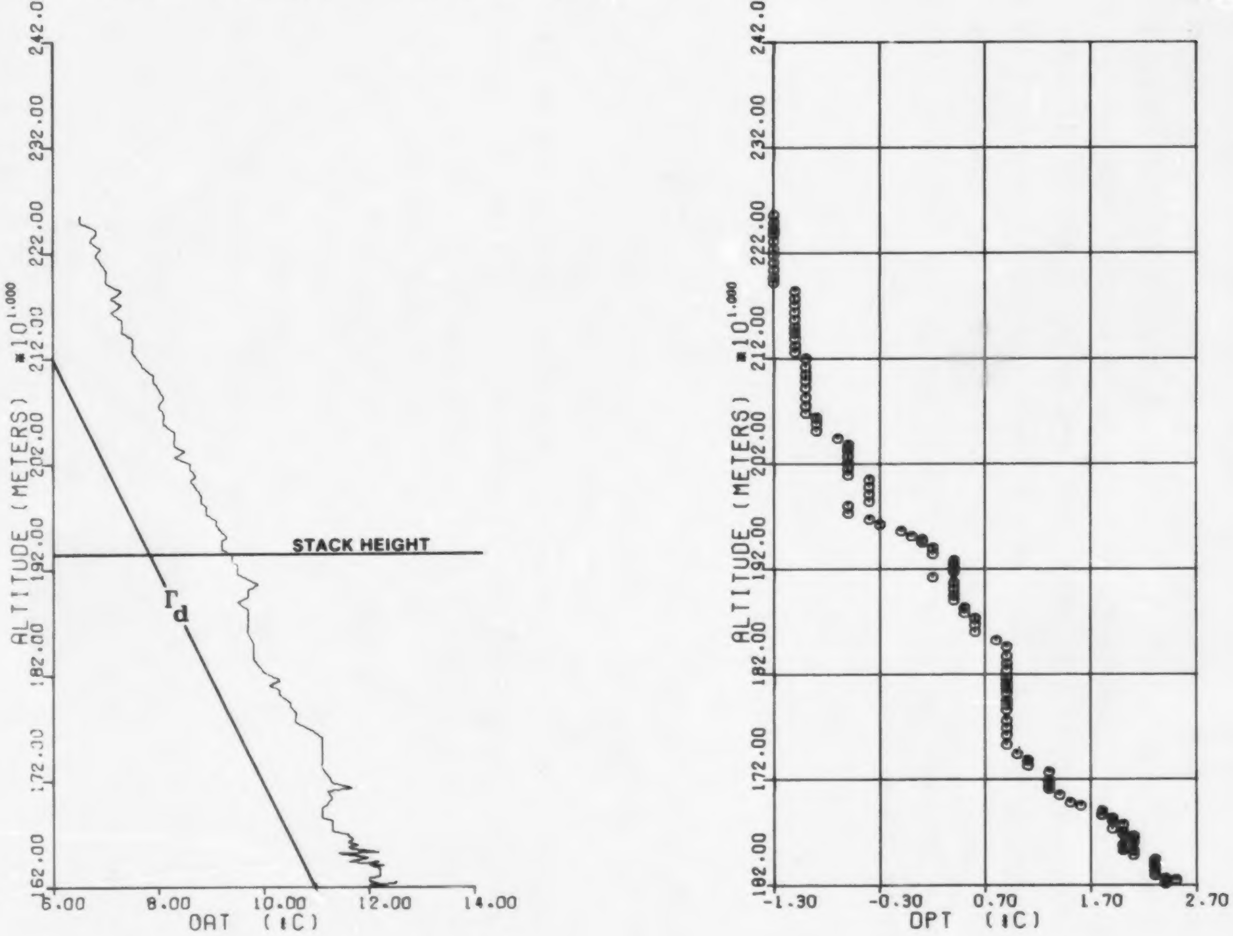

Figure A-86. Temperature and Dewpoint Soundings, 1307 MST, November 9, 1976.

November 10, 1976 0918-1055 MST

The plume was observed impacting upon elevated terrain approximately 6.7 km southwest of the stack. At the beginning of the mission, near isothermal conditions existed at and above stack height and lapse conditions below (Figure A-90). By the end of the mission, neutral conditions existed both above and below the top of the stack and the plume was no longer at the surface (Figure A-91). At the start of the mission, the portable SO_2 monitor had been placed on the hillside in the area of impaction. A series of traverses was made over the monitor by the helicopter at altitudes ranging from 21 to 37 m AGL. Next, a cross section was developed 1.6 km from the stack. A cross section was then made over the transportable monitor. The plume was no longer hitting the hill at this time. Table A-23 summarizes the mission.

TABLE A-23
SUMMARY OF MISSION, NOVEMBER 10, 1976

1. Butte Weather: 0850 10 SCT 28 SCT 40 OVC CLM
2. Plant Emissions, SO_2: 0800-0900 11.8×10^9 μg/s
   0900-1000 8.8×10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 2134 m/ 1.6 km/ 28.4 ppm
   Centerline Height/ Distance/ Concentration: 2160 m/ 6.7 km/ 3.5 ppm
4. Three-minute σ_y, SO_2: 159 m/ 26 m/ 6 cases/ 1.6 km
   834 m/ 225 m/ 7 cases/ 6.7 km
   Three-minute σ_y, B_{scat}: 152 m/ 23 m/ 8 cases/ 1.6 km
5. σ_z, Cross Section, SO_2: 75 m/ 19 min/ 1.6 km
   σ_z, Cross Section, B_{scat}: 85 m/ 19 min/ 1.6 km
6. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0930	1950	014	6
	2130	008	5
1000	1950	014	7
	2130	014	5
1030	1950	011	5
	2130	012	3

Winds Aloft:	Time (MST)	Height (m MSL)	Direction (^{o})	Speed (m/s)
	1100	1950	037	4

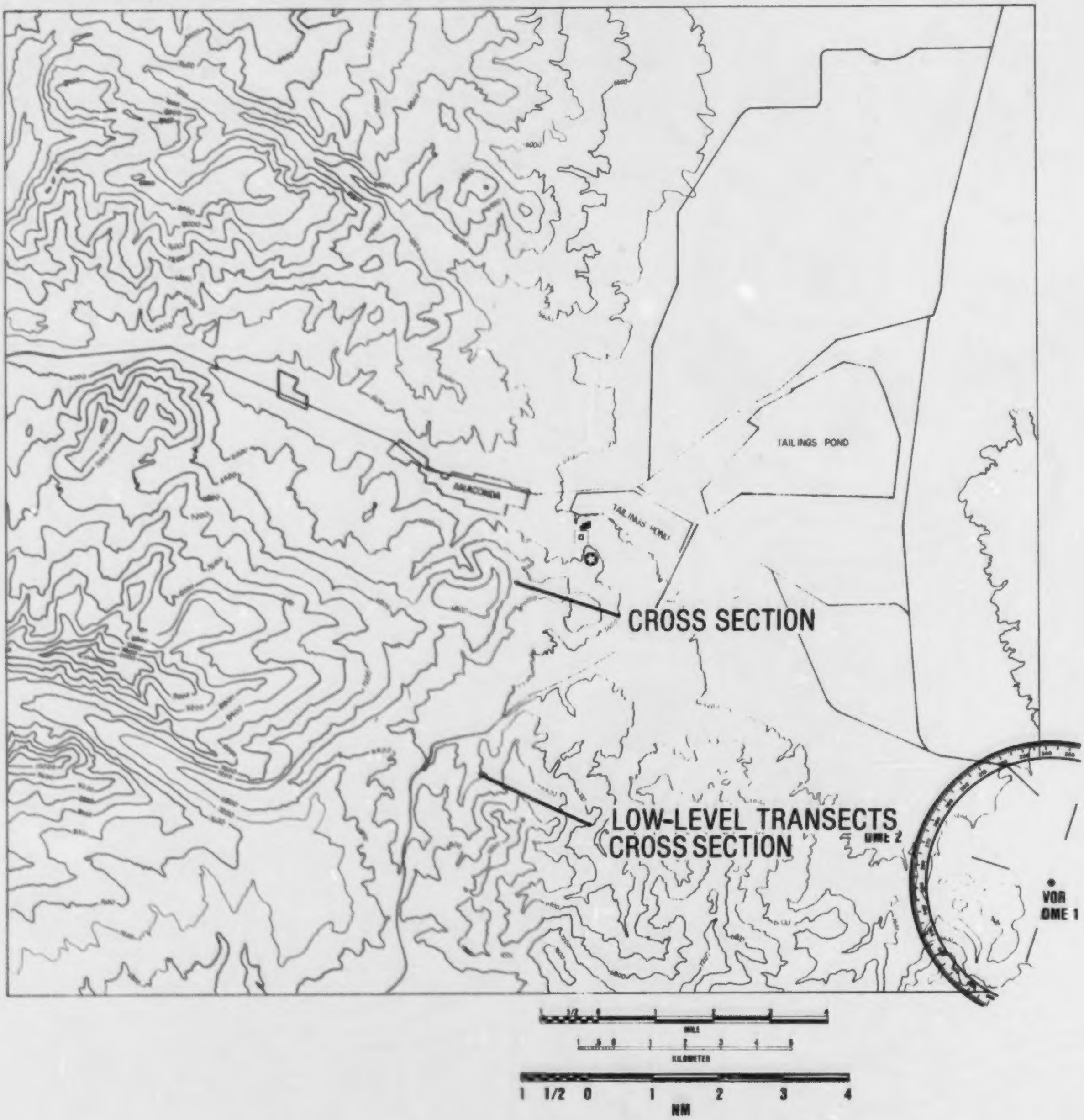

Figure A-87. Sampling Locations, November 10, 1976.

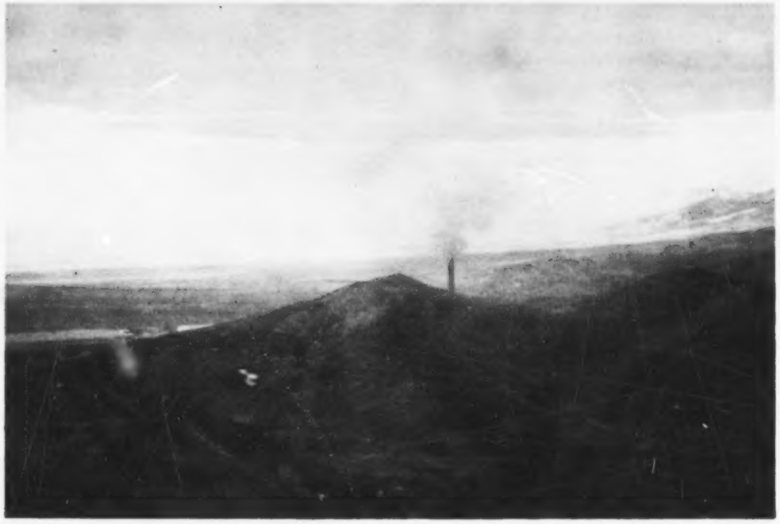

Figure A-88. Plume, November 10, 1976.

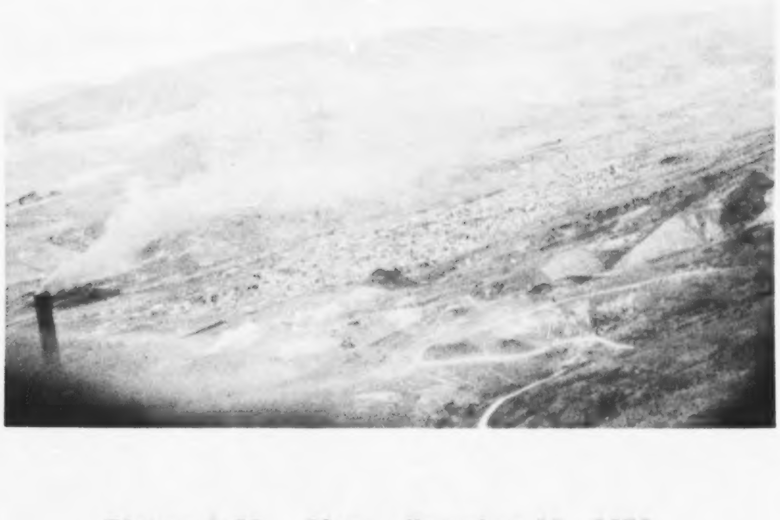

Figure A-89. Plume, November 10, 1976.

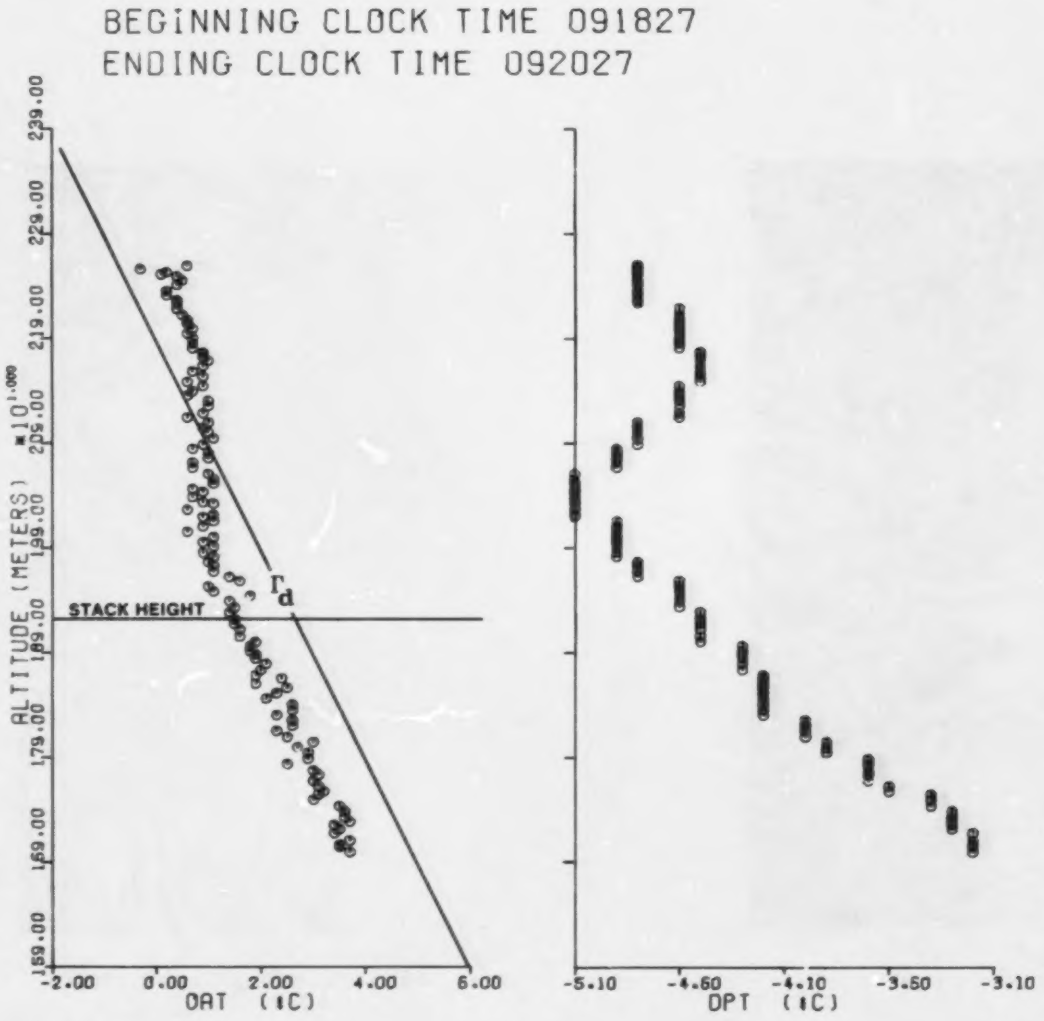

Figure A-90. Temperature and Dewpoint Soundings, 0918 MST, November 10, 1976.

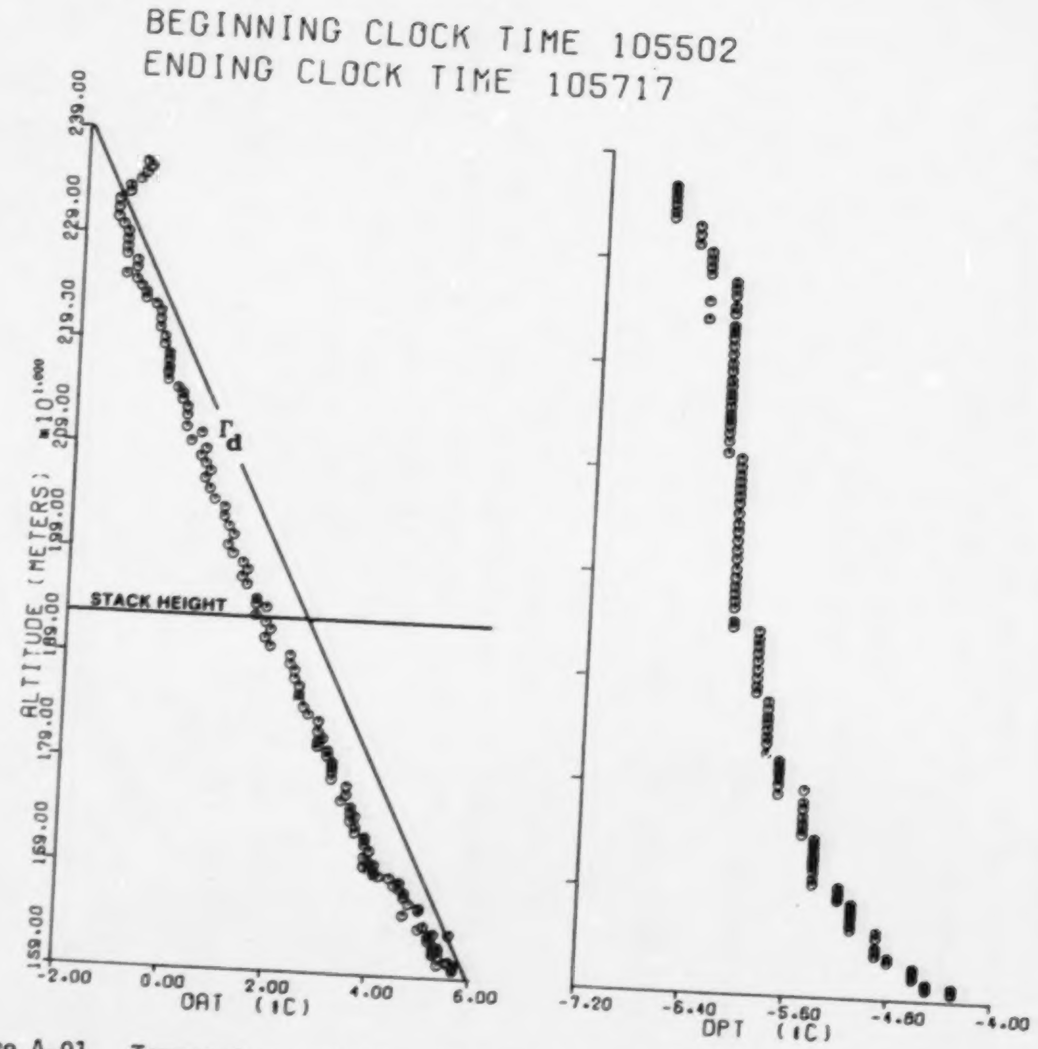

Figure A-91. Temperature and Dewpoint Soundings, 1055 MST, November 10, 1976.

November 11, 1976 0700-0955 MST

Stable conditions (Figure A-95) coupled with low wind speeds resulted in the plume impacting upon elevated terrain approximately 11 km southwest of the stack. A series of low-level traverses were made at altitudes ranging from 2256 to 2454 m MSL along the windward side of the hill. The large values of σ_y that were observed were because the low momentum plume was splitting and going around either side of the hill. A maximum SO_2 value of 12.5 ppm was observed between 30 and 18 m AGL. At approximately 0815 MST, the wind shifted and the plume began to travel in a northwesterly direction. A cross section was developed 1.9 km from the stack.

TABLE A-24
SUMMARY OF MISSION, NOVEMBER 11, 1976

1. Butte Weather: 0656 CLR CLM
   1050 200 SCT 310/4
2. Plant Emissions, SO_2: 0600-0700 16.3×10^9 µg/s
   0700-0800 18.8×10^9 µg/s
   0800-0900 15.6×10^9 µg/s
   0900-1000 15.6×10^9 µg/s
3. Centerline Height/ Distance/ Concentration: 2195 m/ 1.9 km/ 45.3 ppm
   Centerline Height/ Distance/ Concentration: 2316 m/ 10.8 km/ 13.9 ppm
4. Three-minute σ_y, SO_2: 222 m/ 120 m/ 5 cases/ 1.9 km
   691 m/ 70 m/ 7 cases/ 10.8 km
5. σ_z, Cross Section, SO_2: 60 m/ 20 min/ 1.9 km
   σ_z, Cross Section, B_{scat}: 58 m/ 20 min/ 1.9 km
6. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (^{o})	Speed (m/s)
0722	1950	136	2
	2190	121	2
	2310	099	1
0752	1950	165	2
	2190	160	2

Winds Aloft:	Time (MSL)	Height (m MSL)	Direction (^{o})	Speed (m/s)
	0822	1950	183	3
		2190	156	5
		2310	162	2
	0852	1950	177	3
		2190	163	4
		2310	163	3
	0922	1950	182	2
		2190	192	3
		2310	179	3
	0952	1950	174	2
		2190	188	2
		2310	177	2

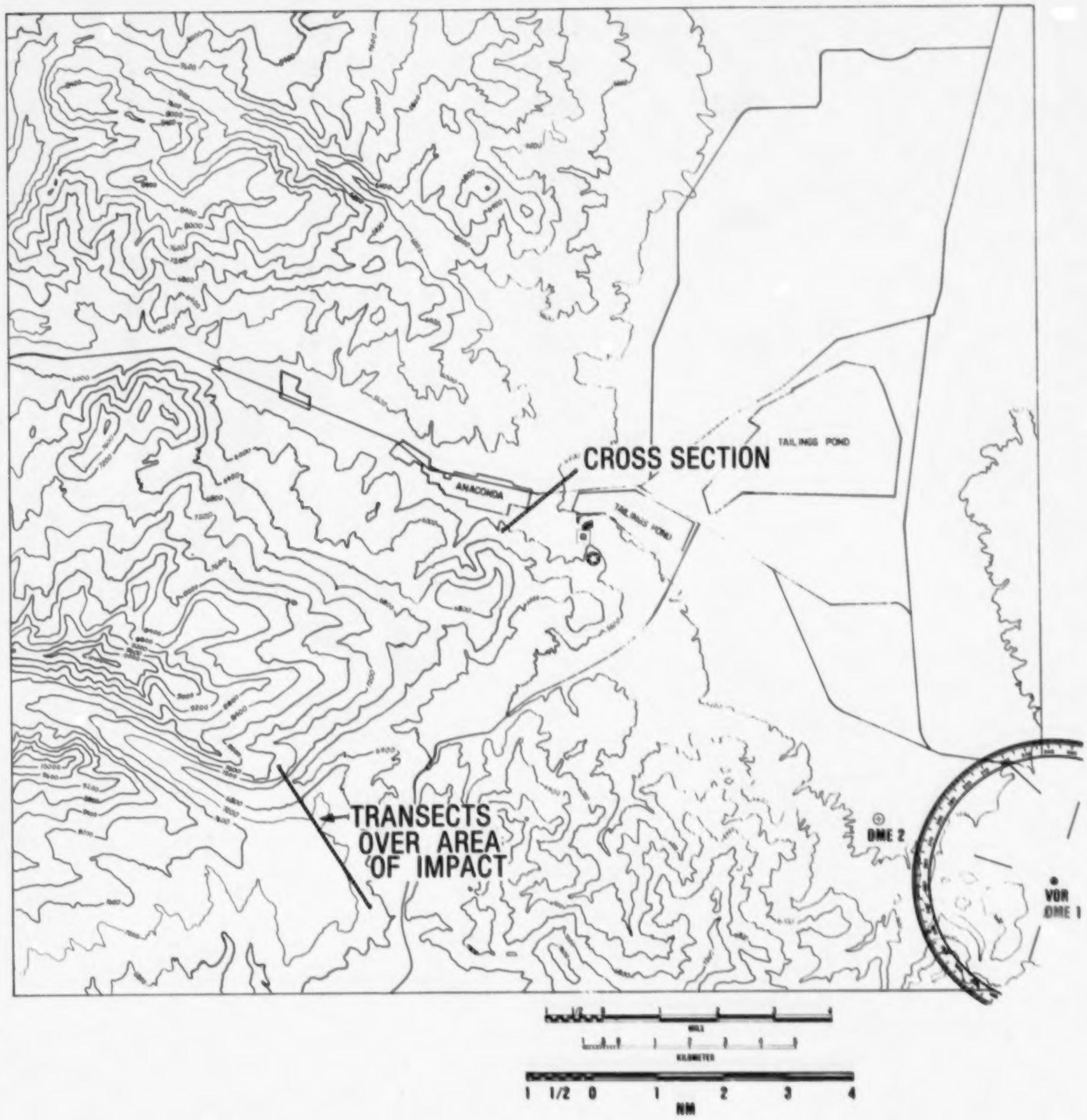

Figure A-92. Sampling Locations, November 11, 1976.

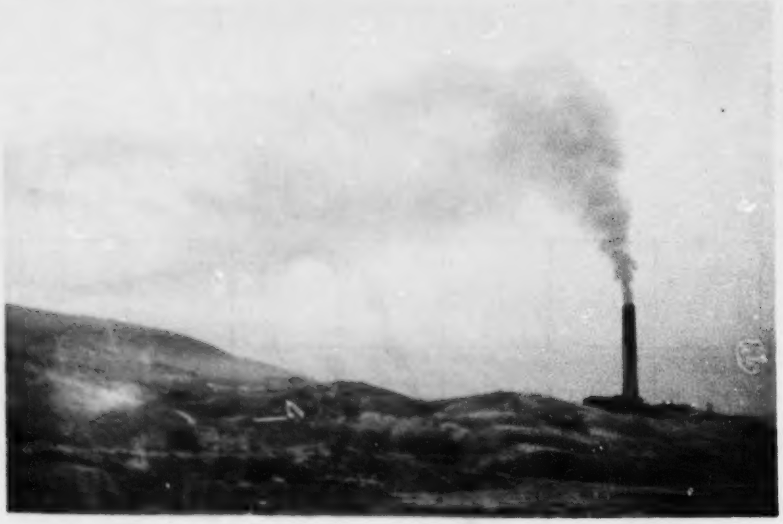

Figure A-93. Plume, November 11, 1976.

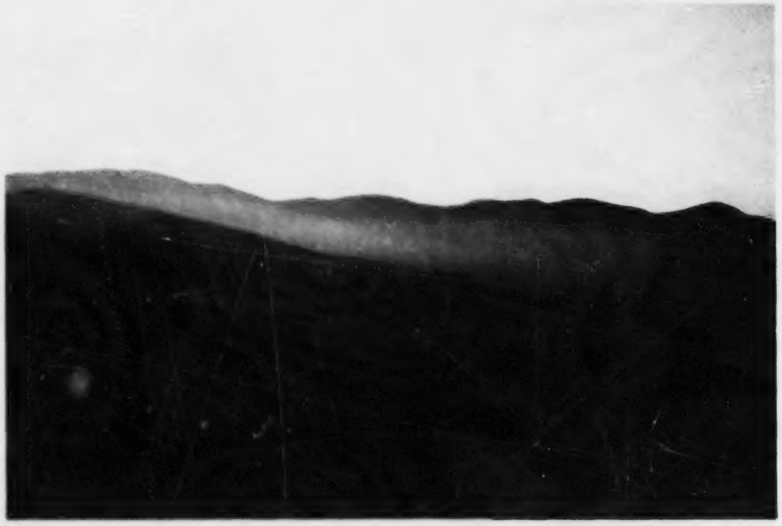

Figure A-94. Plume Impaction, November 11, 1976.

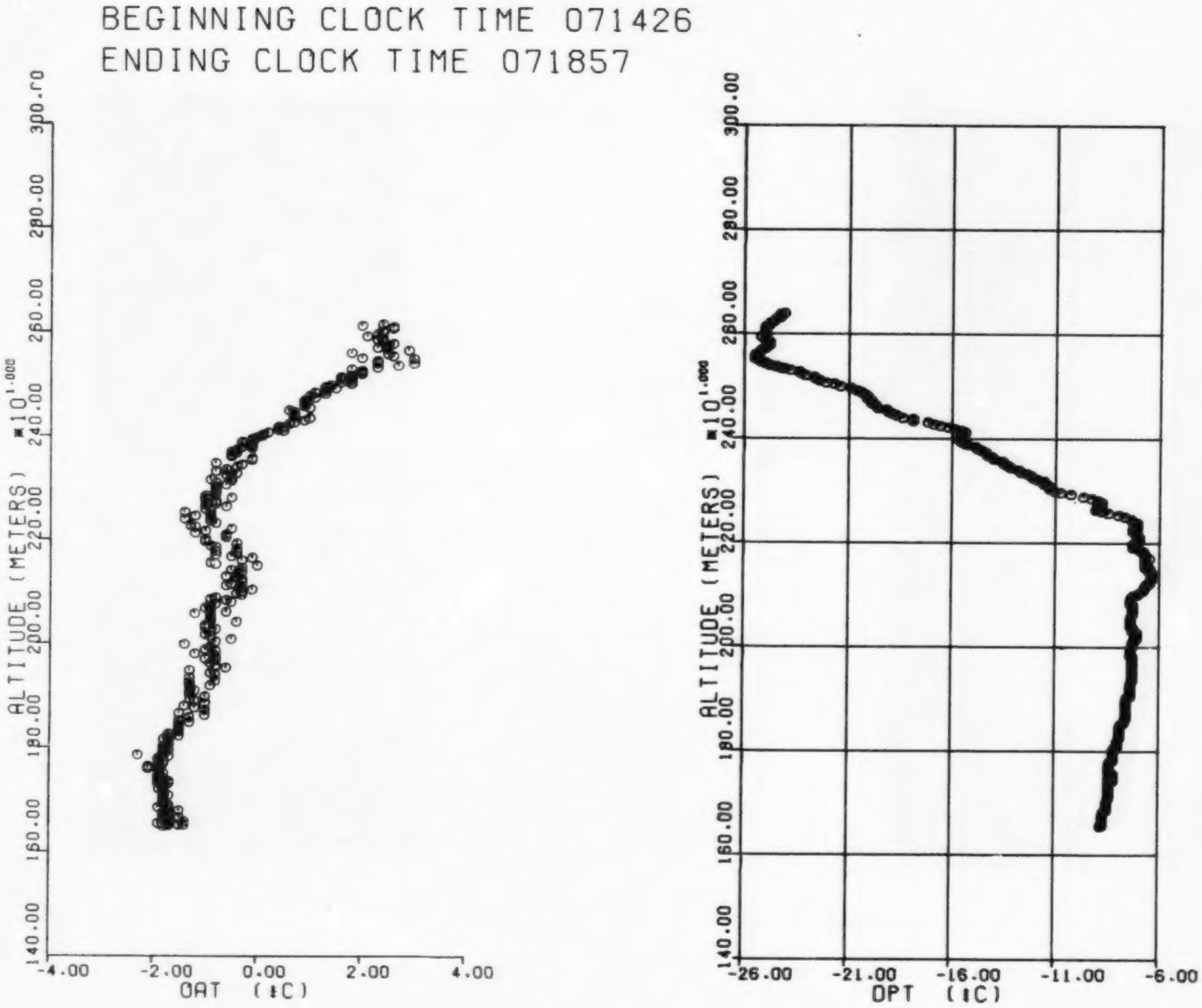

Figure A-95. Temperature and Dewpoint Soundings, 0714 MST, November 11, 1976.

November 12, 1976 0719-0955 MST

The plume was observed impacting upon elevated terrain approximately 8.7 km south-southwest of the stack (Figure A-98). Stable conditions, near isothermal, (Figures A-99 and A-100) and light winds were observed. Two cross sections were developed over the portable SO_2 monitor at approximately 8.7 km and at 1.2 km. Traverses were also made at 31 km. Centerline concentrations as high as 4.8 ppm SO_2 were observed at 31 km. The nephelometer data were questionable.

TABLE A-25
SUMMARY OF MISSION, NOVEMBER 12, 1976

1. Butte Weather: 0651 CLR CLM
   1050 CLR 330/4
2. Plant Emissions, SO_2: 0600-0700 15.3×10^9 μg/s
   0700-0800 11.9×10^9 μg/s
   0800-0900 19.4×10^9 μg/s
   0900-1000 16.7×10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 2347 m/ 1.2 km/ 37.9 ppm
   Centerline Height/ Distance/ Concentration: 2408 m/ 8.7 km/ 14.6 ppm
4. Three-minute σ_y, SO_2: 202 m/ 67 m/ 8 cases/ 1.2 km
   505 m/ 155 m/ 11 cases/ 8.7 km
   758 m/ 359 m/ 2 cases/ 31.0 km
5. σ_z, Cross Section, SO_2: 60 m/ 55 min/ 1.2 km
   100 m/ 22 min/ 8.7 km
6. σ_z, Spiral, SO_2: 43 m/ 4.4 min/ 7.5 km

7. Winds Aloft:	Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
	0720	1950	140	3
		2340	031	3
		2400	041	3
	0751	1950	169	2
		2340	034	3
		2400	032	3
	0820	1950	163	1
		2340	044	2
		2400	055	2
	0850	1950	160	0
		2340	053	2
		2400	063	2
	0920	1950	173	1
		2340	075	2
		2400	088	2
	0950	1950	147	1
		2340	067	2
		2400	082	1

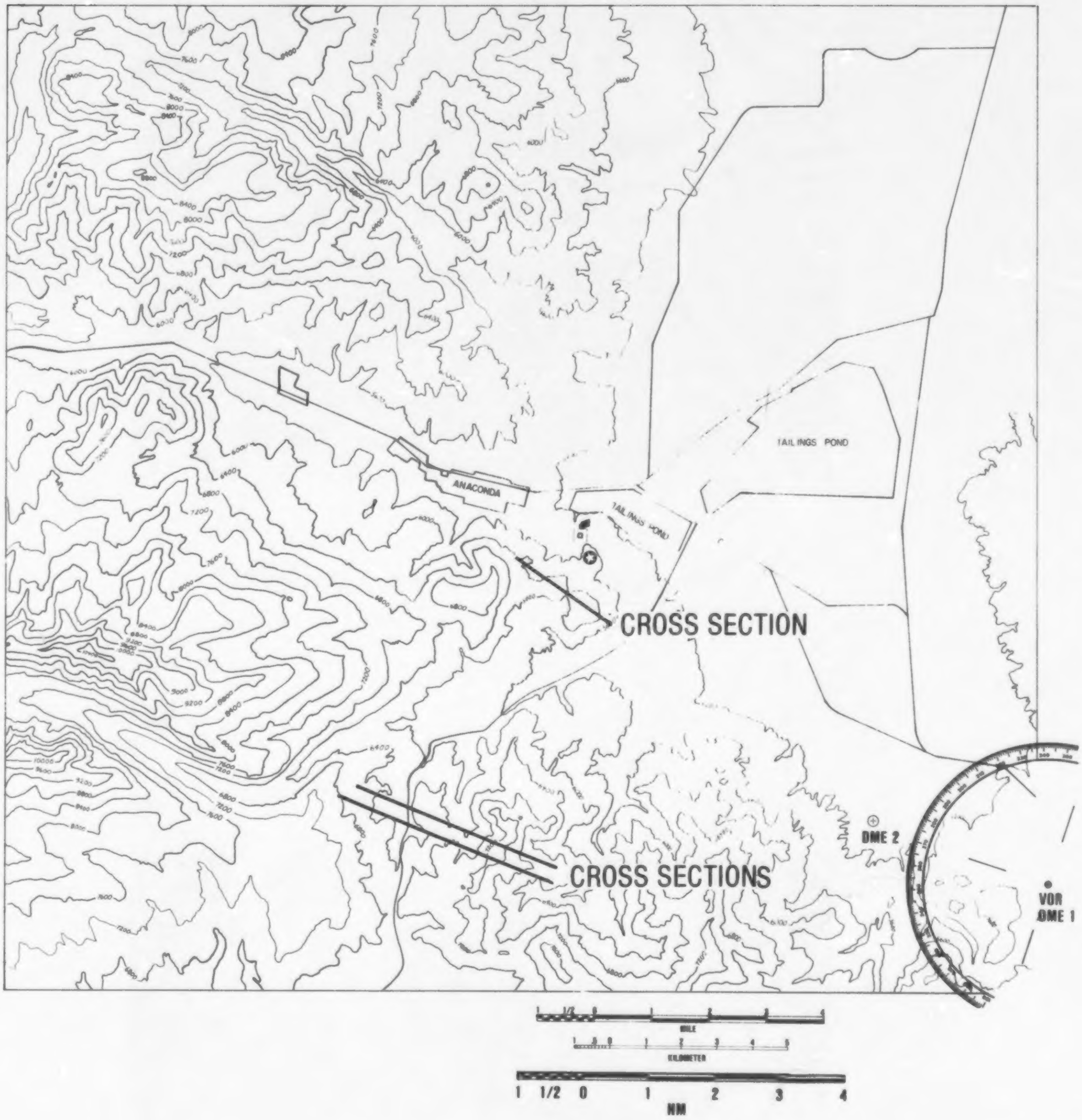

Figure A-96. Sampling Locations, November 12, 1976.

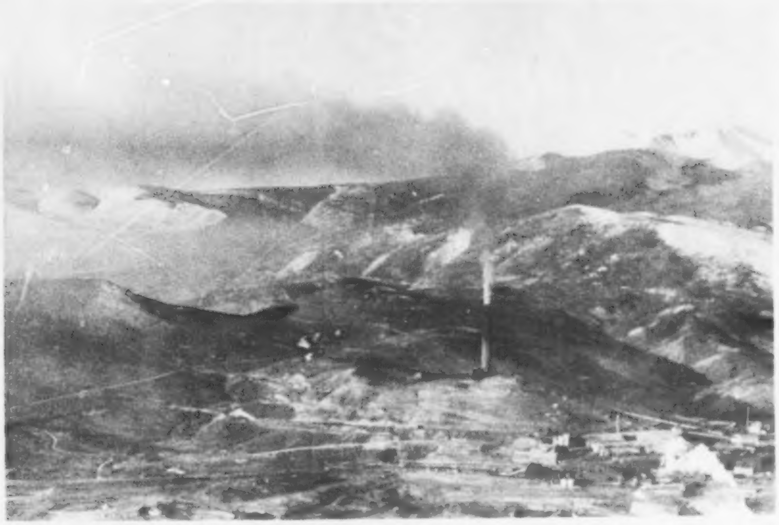

Figure A-97. Plume, November 12, 1976.

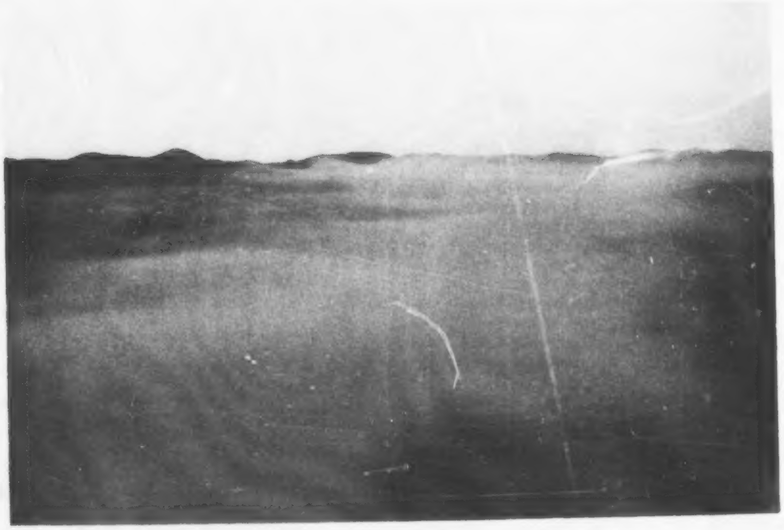

Figure A-98. Plume Under Stable Conditions, November 12, 1976.

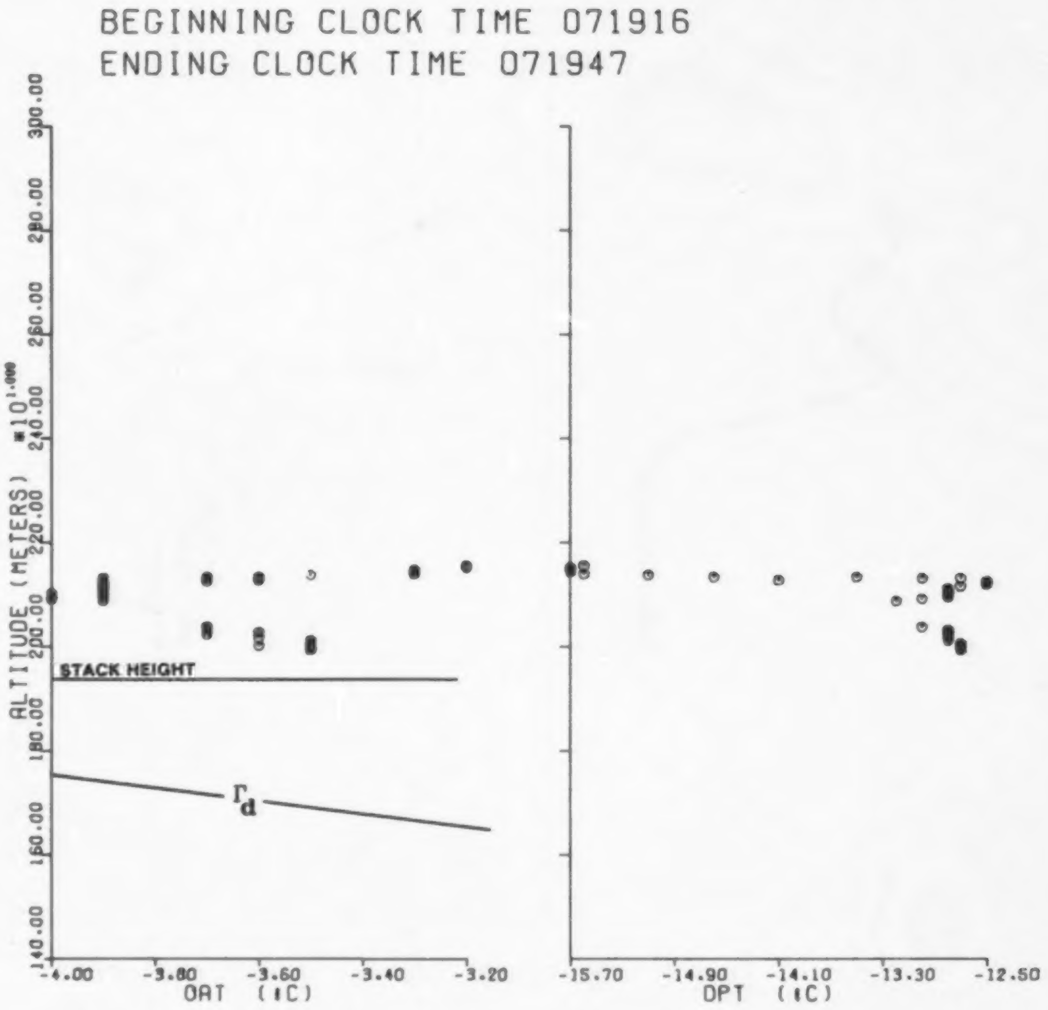

Figure A-99. Temperature and Dewpoint Soundings, 0719 MST, November 12, 1976.

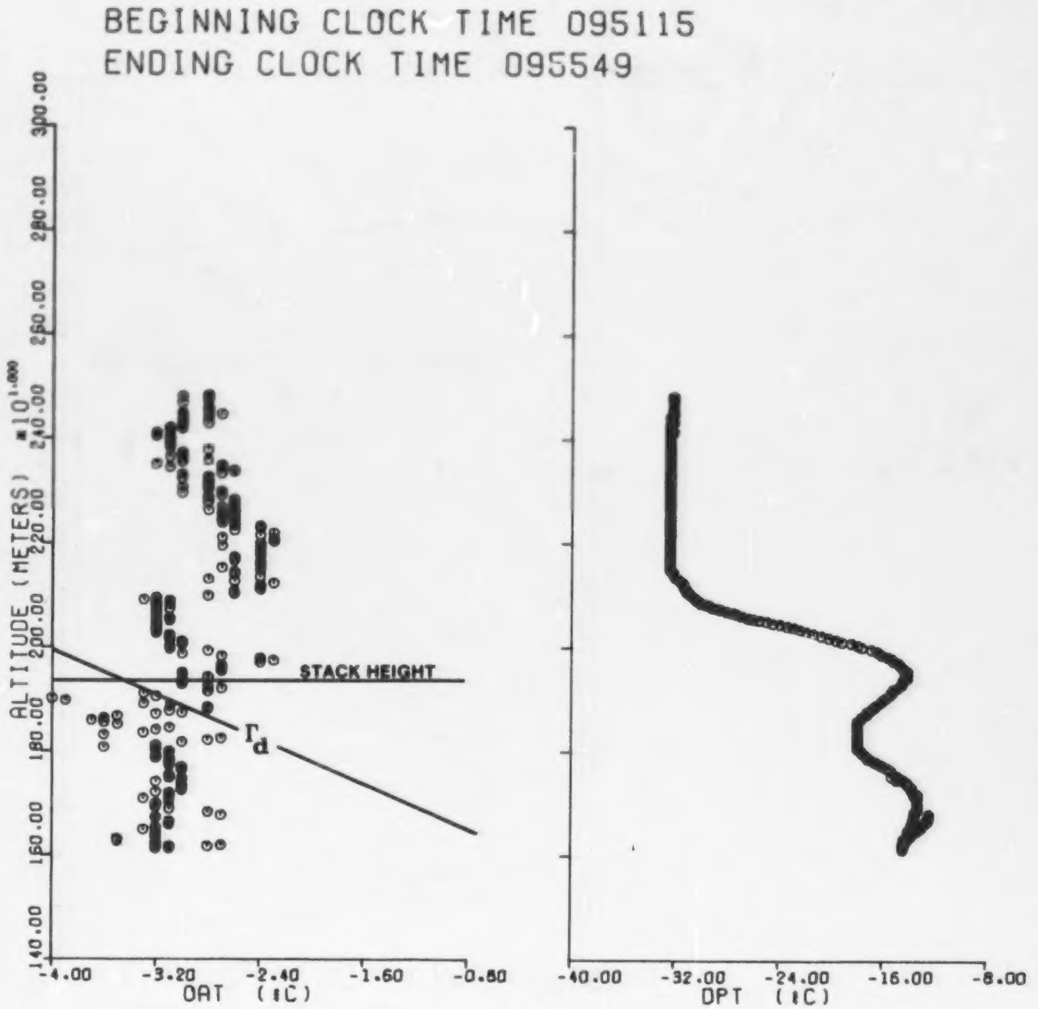

Figure A-100. Temperature and Dewpoint Soundings, 0951 MST, November 12, 1976.

November 13, 1976 0716-0930 MST

Stable conditions were observed during a flight (Figure A-103). Multiple traverses and spirals were made 9.6 km northeast of the stack. In addition, a zigzag pattern was flown up the plume at approximately the height of the plume centerline, 2073 m MSL. Beginning at 1.6 km from the stack, the helicopter flew through the plume at an angle 45° to the axis. As soon as the aircraft left the plume, it executed a 270° turn and re-entered the plume at the same location. This was done until a distance of 32 km was reached.

TABLE A-26
SUMMARY OF MISSION, NOVEMBER 13, 1976

1. Butte Weather: 0652 CLR 160/05
   1052 CLR 040/03
2. Plant Emissions, SO_2: 0600-0700 11.3×10^9 μg/s
   0700-0800 10.3×10^9 μg/s
   0800-0900 14.1×10^9 μg/s
   0900-1000 18.1×10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 2069 m/ 9.6 km/ 16.7 ppm
4. Three-minute σ_y, SO_2: 528 m/ 6[illegible] m/ 7 cases/ 9.6 km
5. σ_z, Spiral, SO_2: 28 m/ 3.3 min/ 9.6 km
   σ_z, Spiral, SO_2: 32 m/ 3.3 min/ 9.6 km
   σ_z, Spiral, SO_2: 36 m/ 3.8 min/ 9.6 km
   σ_z, Spiral, SO_2: 39 m/ 3.3 min/ 9.6 km
6. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0800	1950	219	8
	2070	227	10
0830	1950	193	14
	2070	208	9
0900	1950	207	6
	2070	215	9
0930	1950	212	12
	2070	215	7

Winds Aloft:	Time (MST)	Height (m MSL)	Direction (^{o})	Speed (m/s)
	1000	1950	222	9
		2070	223	13
	1030	1950	225	7
		2070	224	11

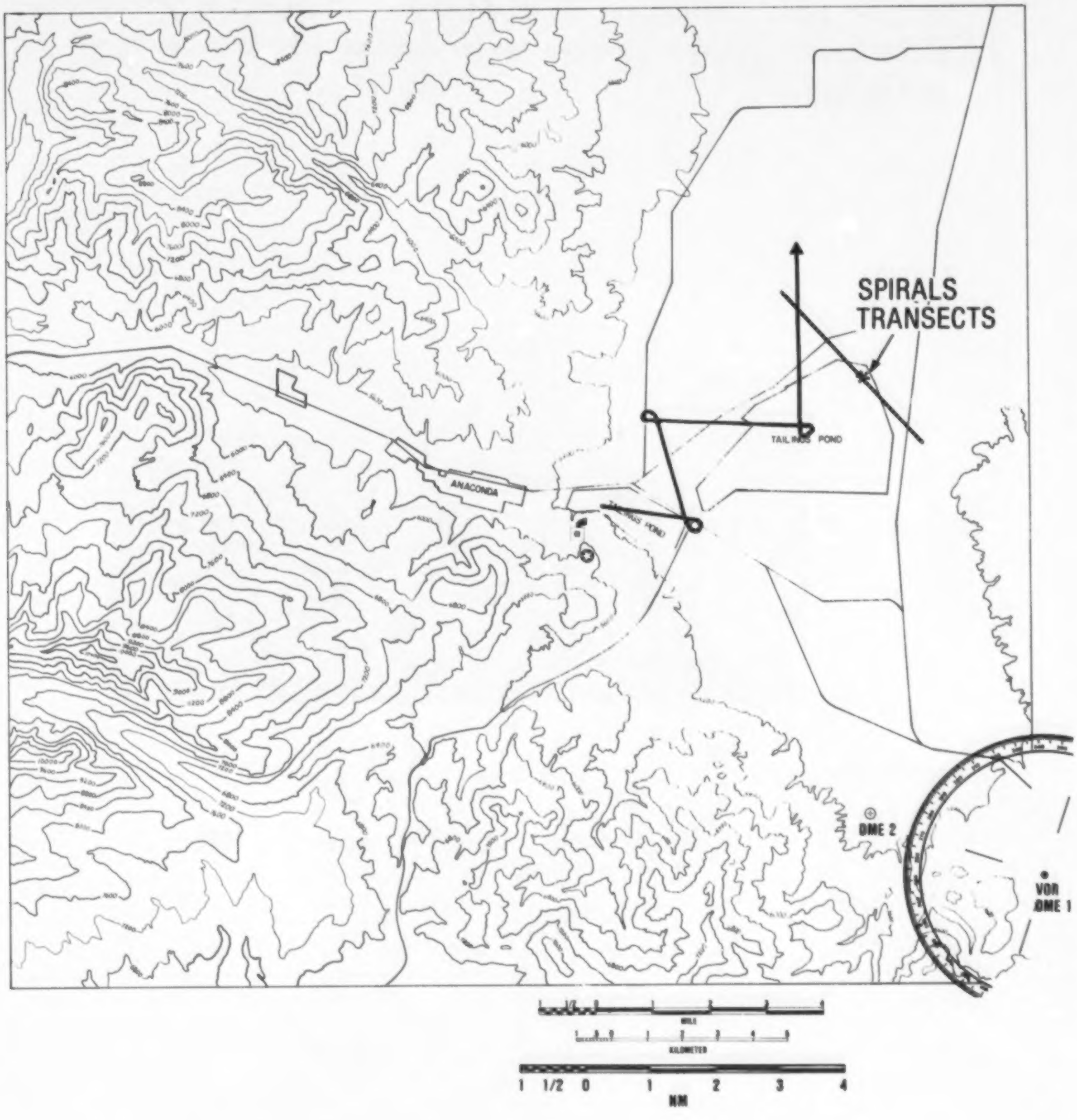

Figure A-101. Sampling Locations, November 13, 1976.

Tables A-27 and A-28 summarize the zig zag flight down the plume. Values for σ_y were determined by the relationship that 2.15 σ is the distance from centerline to 1/10 of centerline. The results were then adjusted using a simple cosine relationship. At distances greater than 5.5 km the plume was fragmented and an exact determination of σ_y was difficult.

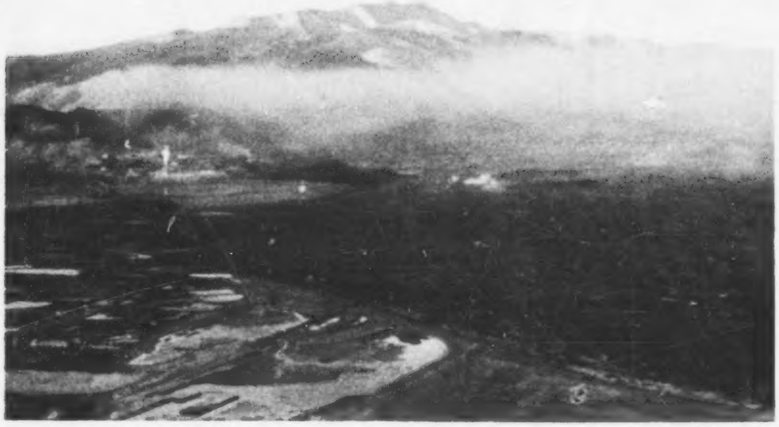

Figure A-102. Plume, November 13, 1976.

TABLE A-27
DISTANCE VS. OBSERVED SO_2 MAXIMUM

Distance (km)	SO_2 Maximum (ppm)
0.7	15.6
1.8	42.0
3.0	11.5
4.2	3.27
5.5	4.80
11.1	2.65
13.1	1.70
17.1	3.06
25.8	2.46

TABLE A-28
DISTANCE VS. σ_y (SO_2), TRANSECT (m)

Distance (km)	σ_y(m)
0.7	71
1.8	71
3.0	132
4.2	275
5.5	346
11.1	219
17.1	642
25.8	500

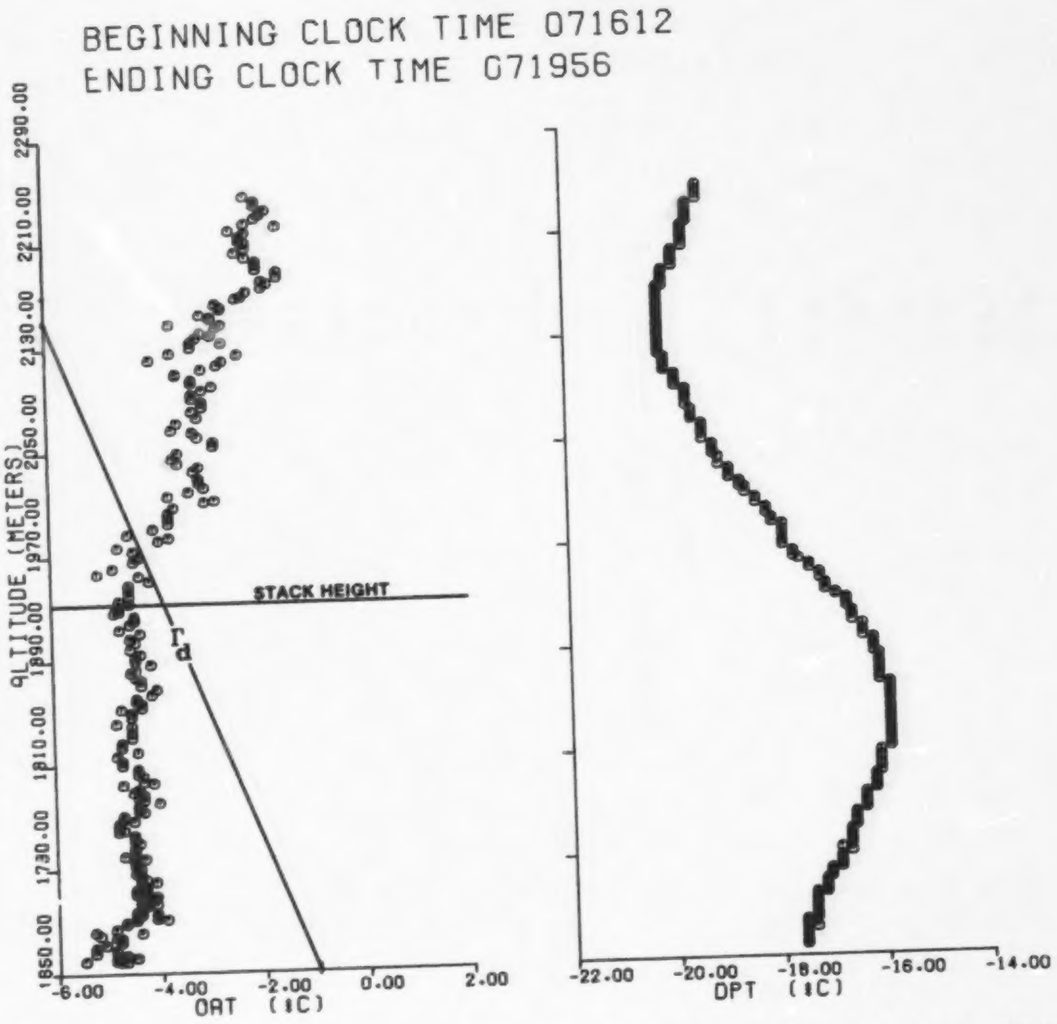

Figure A-103. Temperature and Dewpoint Soundings, 0716 MST, November 13, 1976.

November 15, 1976 0727-0918 MST

Strong winds caused a bentover plume (Figure A-105). Vortices occasionally formed on the lee side of the stack causing impaction in the smelter area (Figure A-106). An attempt was made to construct cross sections in the vicinity of the impaction area over the tailings pond immediately to the east of the smelter and over the transportable SO_2 monitor 3 km northeast of the stack. The temperature probe was not operational. In addition, high background levels of particulates made the interpretation of the nephelometer data questionable. Table A-29 summarizes the mission. No determination of σ_z was possible.

TABLE A-29

SUMMARY OF MISSION, NOVEMBER 15, 1976

1. Butte Weather: 0652 100 SCT CLM
   0950 60 BRKN 030/5
2. Plant Emissions, SO_2: 0630-0730 16.9×10^9 µg/s
   0730-0830 12.2×10^9 µg/s
   0830-0930 16.0×10^9 µg/s
   0930-1030 17.4×10^9 µg/s
3. Centerline Height/ Distance/ Concentration: 1798 m/ 1.8 km/ 22.6 ppm
4. Three-minute σ_y, SO_2: 240 m/ 117 m/ 10 cases/ 1.8 km
   Three-minute σ_y, SO_2: 255 m/ 95 m/ 4 cases/ 3.0 km
5. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0733	1800	236	9
	1950	258	3
0803	1800	235	10
	1950	249	6
0833	1800	233	14
	1950	240	14
0903	1800	251	9
	1950	265	10
0933	1800	237	8
	1950	250	14

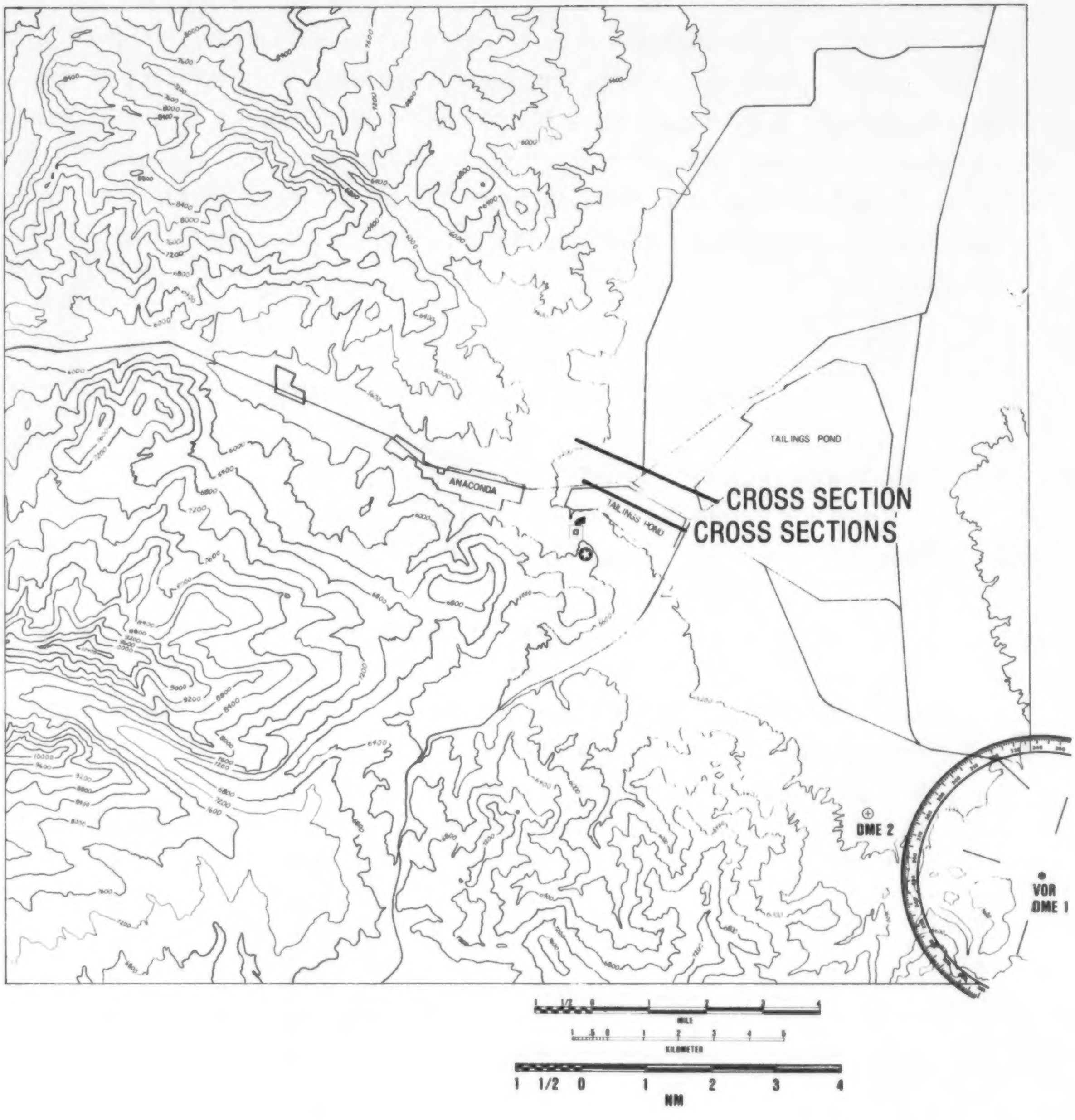

Figure A-104. Sampling Locations, November 15, 1976.

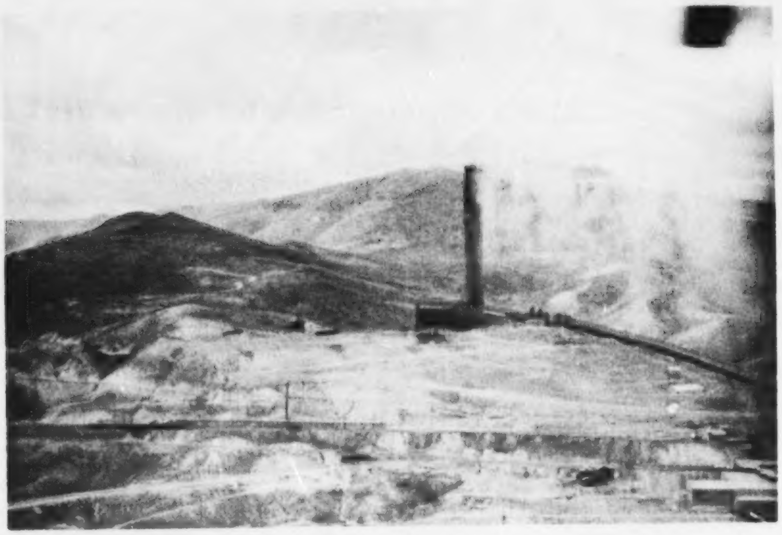

Figure A-105. Plume, November 15, 1976.

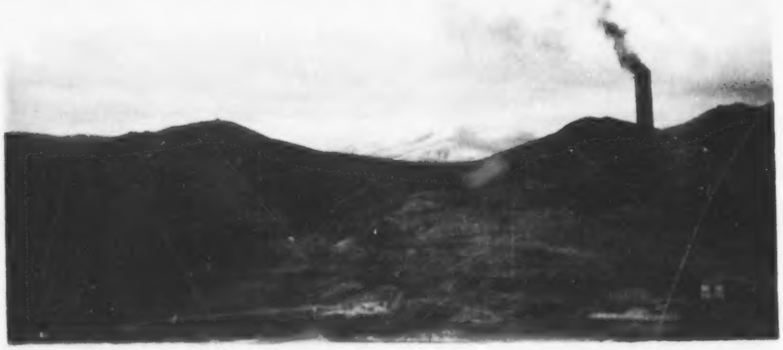

Figure A-106. Plume, November 15, 1976.

November 16, 1976 0723-0843 MST

Stable conditions below stack height coupled with neutral conditions above (Figure A-110), initially produced a lofted plume (Figure A-108). By the end of the mission (Figure A-111), stable conditions observed at stack height coupled with a superadiabatic layer below produced fumigation through the layer. The surface was insulated from the plume by a stable layer throughout the flight. Moderate to strong turbulence was experienced at the juncture of the stable and unstable layers. Higher wind speeds were measured below stack height than near stack height.

TABLE A-30
SUMMARY OF MISSION, NOVEMBER 16, 1976

1. Butte Weather: 0650 55 BRKN 100 BRKN 350/08
   0953 45 SCT 100 BRKN 350/08
2. Plant Emissions, SO_2: 0600-0700 13.9×10^9 μg/s
   0700-0800 13.4×10^9 μg/s
   0800-0900 18.1×10^9 μg/s
   0900-1000 18.5×10^9 μg/s
   1000-1100 15.6×10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 1798 m/ 1.5 km/ 37.4 ppm
4. Three-minute σ_y, SO_2: 144 m/ 68 m/ 3 cases/ 1.3 km
   Three-minute σ_y, B_{scat}: 190 m/ 109 m/ 4 cases/ 1.3 km
   Three-minute σ_y, SO_2: 141 m/ 17 m/ 7 cases/ 1.5 km
   Three-minute σ_y, B_{scat}: 130 m/ 39 m/ 8 cases/ 1.5 km
   Three-minute σ_y, SO_2: 133 m/ 28 m/ 6 cases/ 2.6 km
   Three-minute σ_y, B_{scat}: 149 m/ 80 m/ 7 cases/ 2.6 km
   Three-minute σ_y, SO_2: 260 m/ 87 m/ 6 cases/ 6.4 km
   Three-minute σ_y, B_{scat}: 324 m/ 54 m/ 6 cases 6.4 km
   Three-minute σ_y, SO_2: 279 m/ ----/ 1 case/ 9.7 km
   Three-minute σ_y, B_{scat}: 267 m/ ----/ 1 case/ 9.7 km

5. σ_z, Cross Section, SO_2: 61 m/ 14 min/ 1.5 km
σ_z, Cross Section, SO_2: 53 m/ 19 min/ 2.6 km
σ_z, Cross Section, B_{scat}: 65 m/ 19 min/ 2.6 km

6. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (^{o})	Speed (m/s)
0726	1800	242	16
	1950	249	16
0756	1800	248	12
	1950	267	6
0830	1800	247	7
	1950	252	6
0900	1800	236	15
	1950	239	10

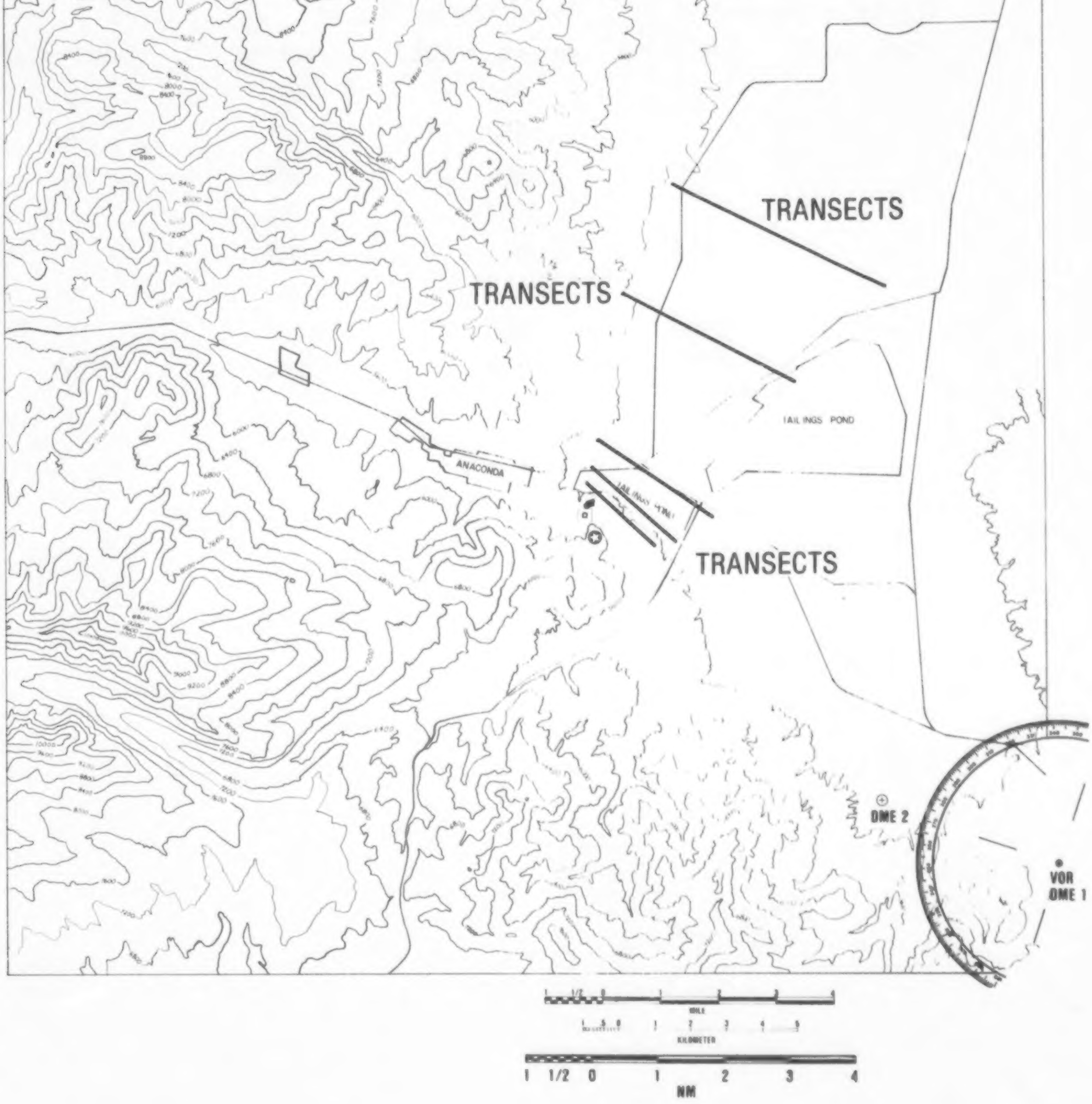

Figure A-107. Sampling Locations, November 16, 1976.

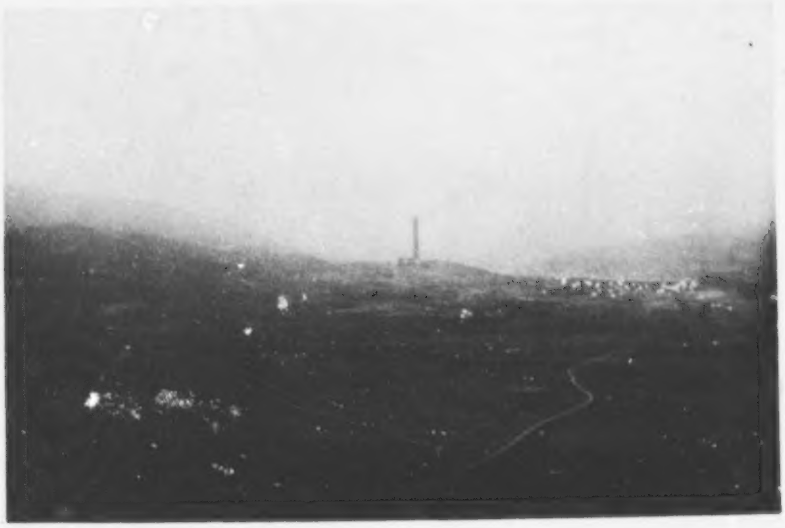

Figure A-108. Plume, November 16, 1976.

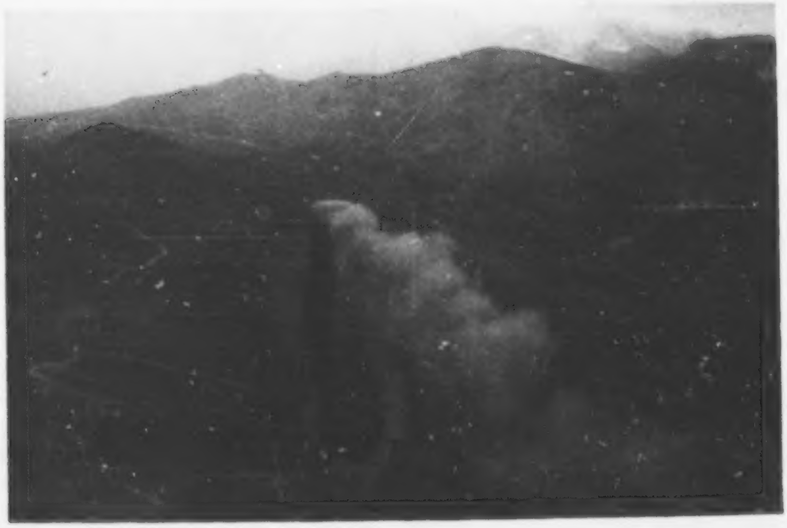

Figure A-109. Plume, November 16, 1976.

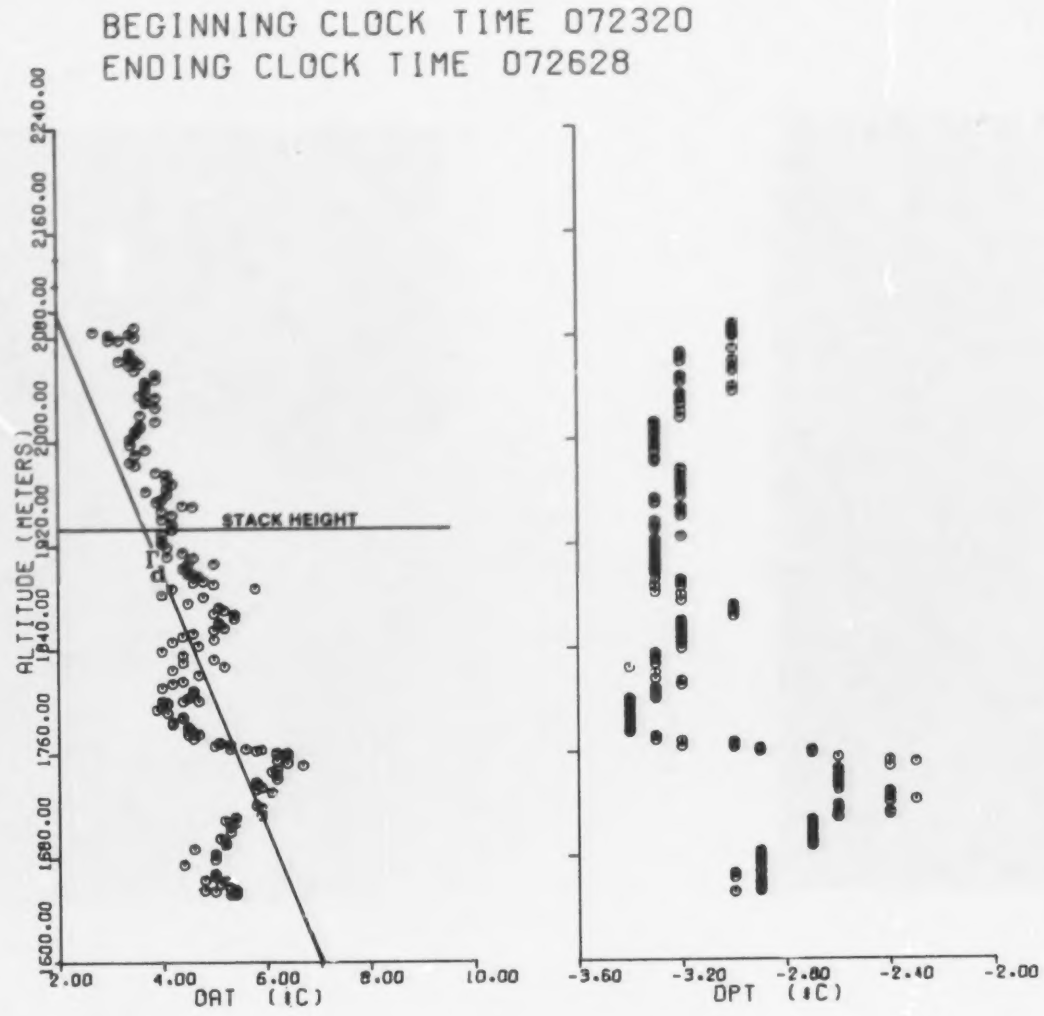

Figure A-110. Temperature and Dewpoint Soundings, 0723 MST, November 16, 1976.

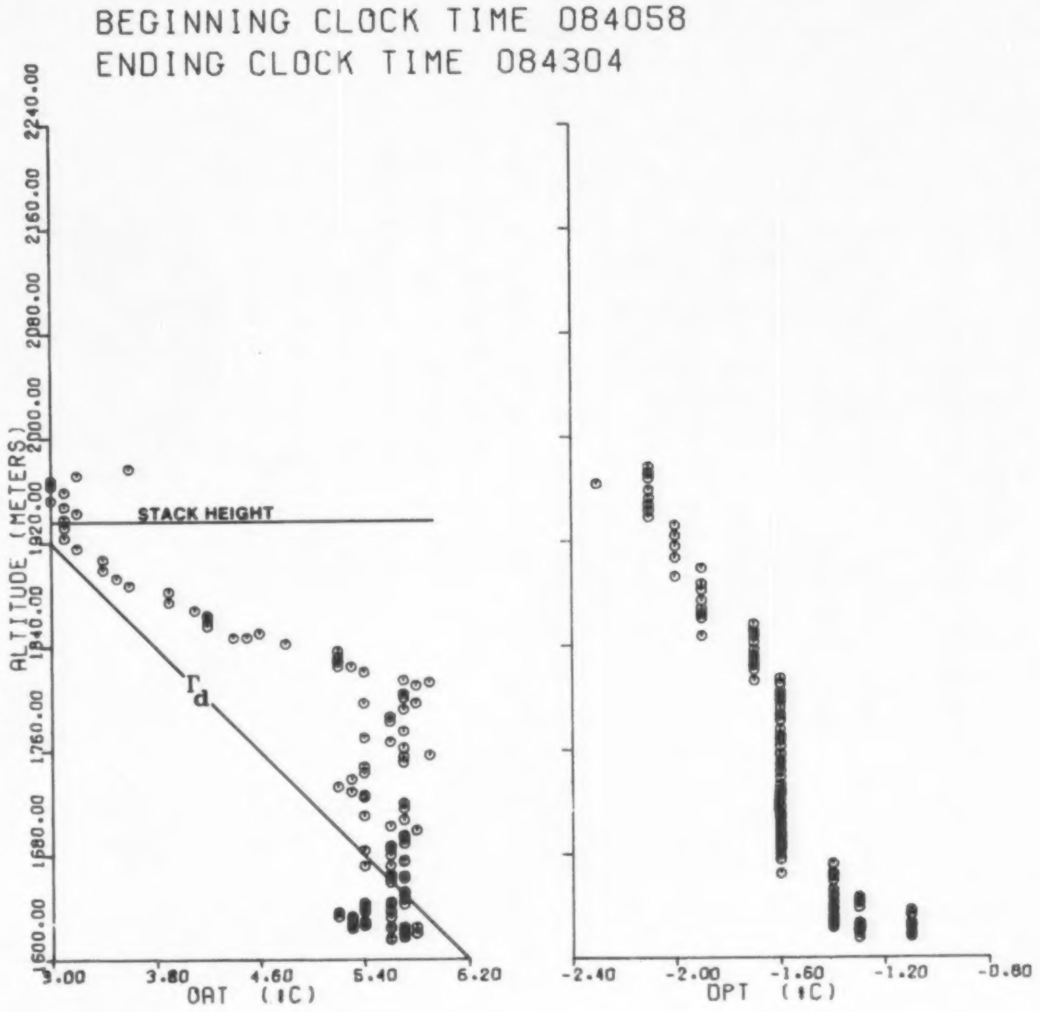

Figure A-111. Temperature and Dewpoint Soundings, 0840 MST, November 16, 1976.

November 17, 1976 0718-0912 MST

At the beginning of the mission, stable conditions existed below stack height with neutral conditions above (Figure A-115). By the end of the mission, stable conditions existed both above and below stack height Figure A-116). Strong winds were observed with downwash conditions (Figures A-113 and A-114). Cross sections were developed at 2.5 and 6.0 km.

TABLE A-31
SUMMARY OF MISSION, NOVEMBER 17, 1976

1. Butte Weather: 0653 50 SCT 120 SCT 200 SCT 170/04
   0950 100 SCT 250 BRKN CLM
2. Plant Emissions, SO_2: 0600-0700 19.3×10^9 μg/s
   0700-0800 17.2×10^9 μg/s
   0800-0900 18.4×10^9 μg/s
   0900-1000 20.1×10^9 μg/s
   1000-1100 15.7×10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 1737 m/ 2.5 km 2.4 ppm
4. Three-minute σ_y, SO_2: 287 m/ 87 m/ 11 cases/ 2.5 km
   Three-minute σ_y, B_{scat}: 340 m/ 160 m/ 13 cases/ 2.5 km
   Three-minute σ_y, SO_2: 481 m/ 96 m/ 14 cases/ 6.0 km
   Three-minute σ_y, B_{scat}: 446 m/ 121 m/ 14 cases/ 6.0 km
5. σ_z, Cross Section, SO_2: 113 m/ 34 min/ 2.5 km
   σ_z, Cross Section, B_{scat}: 142 m/ 34 min/ 2.5 km
   σ_y, Cross Section, SO_2: 133 m /50 min/ 6.0 km
   σ_y, Cross Section, B_{scat}: 121 m/ 50 min/ 6.0 km

6. Winds Aloft:

Time (MST)	Height (m MSL)	Direction (°)	Speed (m/s)
0726	1740	232	15
	1950	239	6
0756	1740	229	11
	1950	226	31
0826	1740	224	16
	1950	221	16
0926	1740	229	8
	1950	242	3
0956	1740	228	18
	1950	222	17
1026	1740	225	6
	1950	233	28
1156	1740	234	15
	1950	248	22

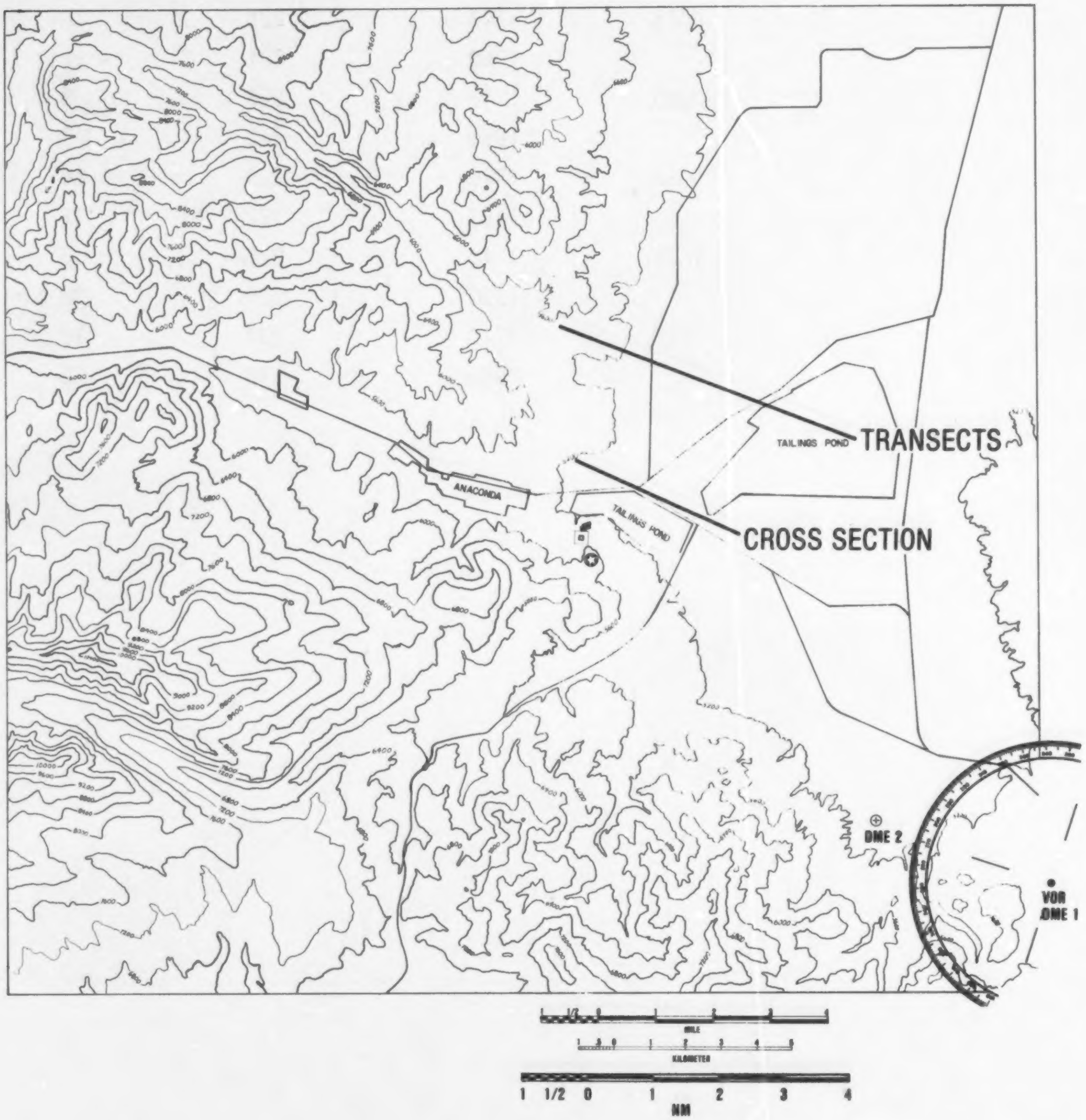

Figure A-112. Sampling Locations, November 17, 1976.

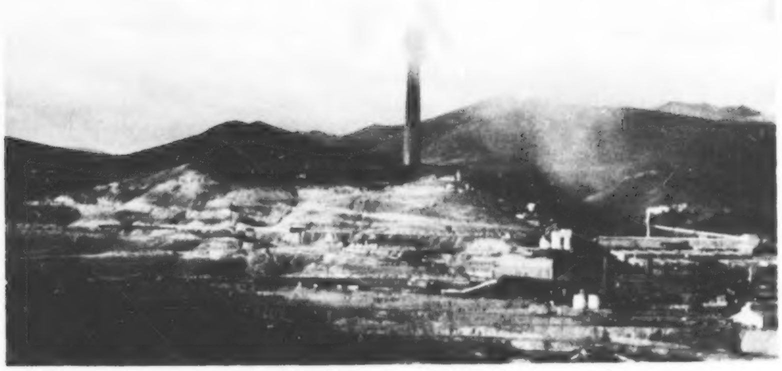

Figure A-113. Plume, November 17, 1976.

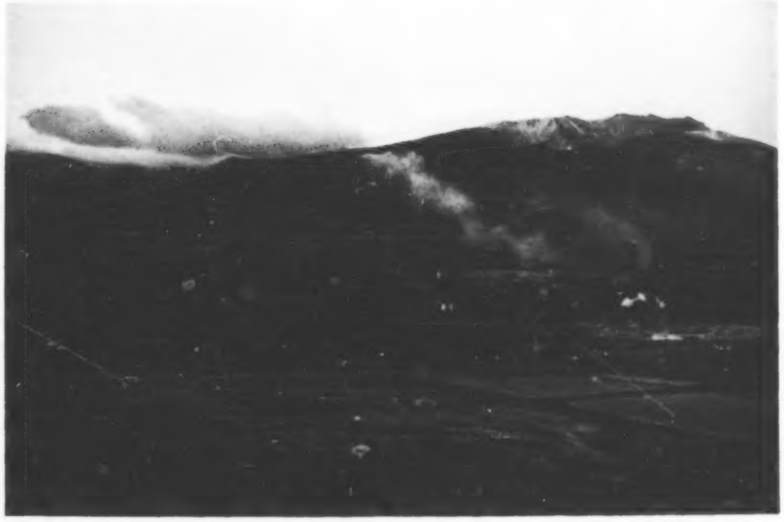

Figure A-114. Plume, November 17, 1976.

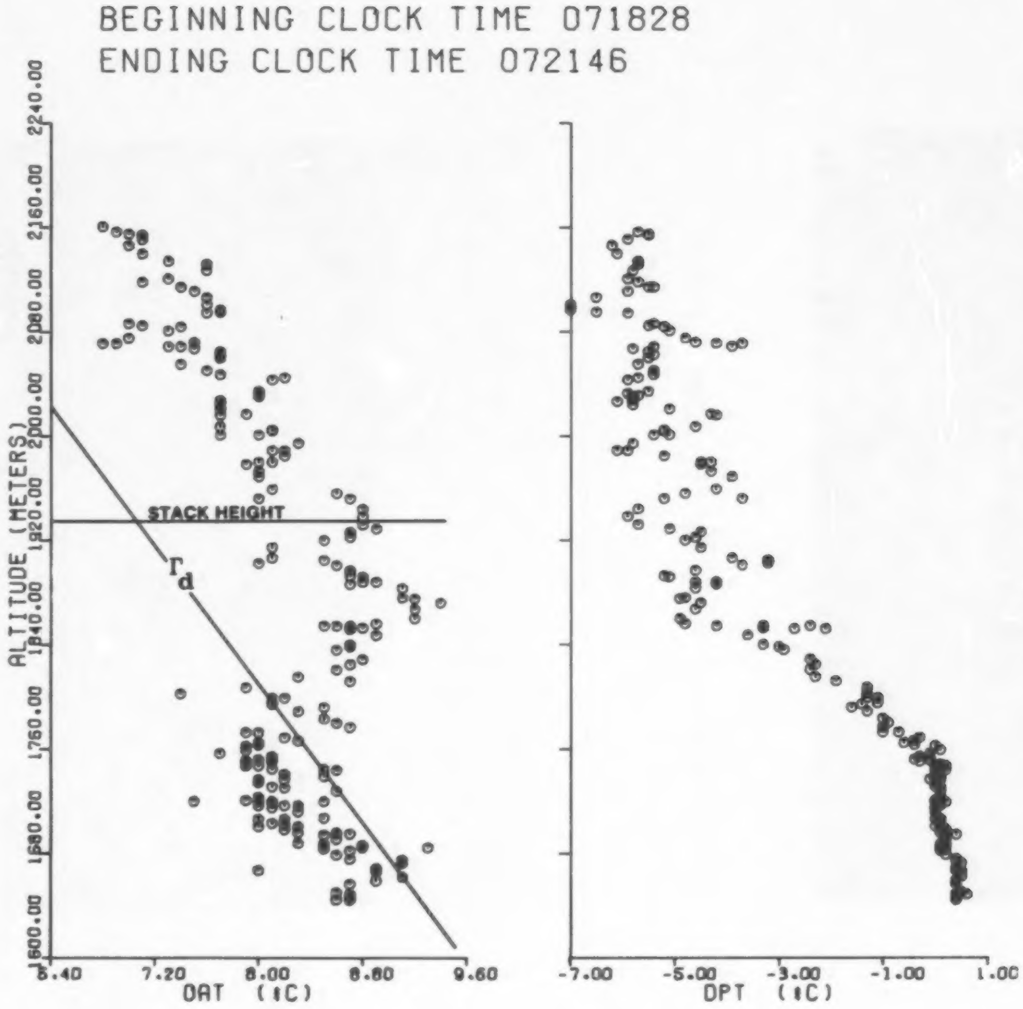

Figure A-115. Temperature and Dewpoint Soundings, 0718 MST, November 17, 1976.

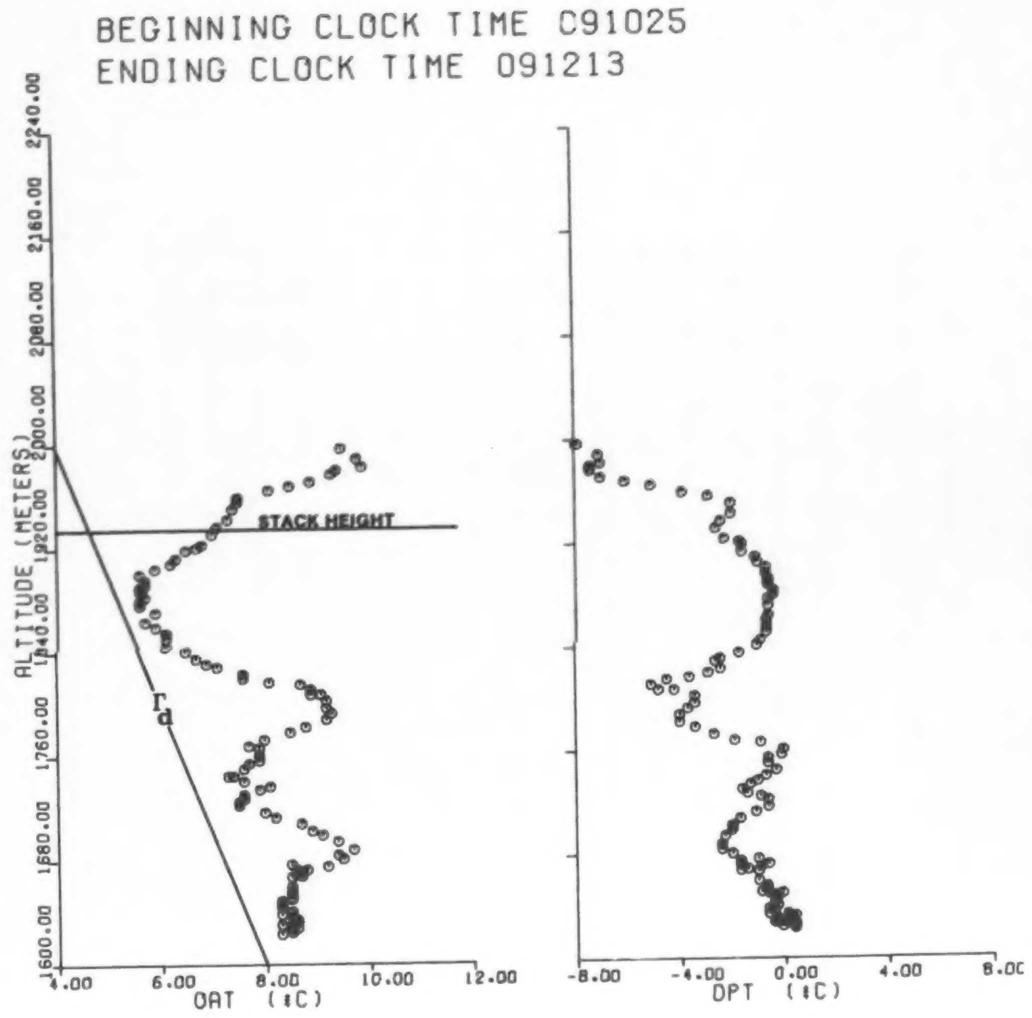

Figure A-116. Temperature and Dewpoint Soundings, 0910 MST, November 17, 1976.

December 3, 1976 0740-1010 MST

Stable conditions due to subsiding air (Figures A-119 and A-120) coupled with strong flow produced downwash conditions (Figure A-118) and occasional plume impaction within 2.0 km of the stack. A cross section was developed 1.7 km east-southeast of the stack. In addition, multiple spirals and traverses were made 6.3 east-southeast of the stack.

TABLE A-32

SUMMARY OF MISSION, DECEMBER 3, 1976

1. Butte Weather: 0651 120 SCT 250 SCT CLM
Plant Emissions, SO_2: 0630-0730 21.3 X 10^9 μg/s
0730-0830 13.9 X 10^9 μg/s
0830-0930 16.8 X 10^9 μg/s
0930-1030 12.6 X 10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 2042 m/ 1.7 km/ 23.0 ppm
4. Three-minute σ_y, SO_2: 185 m/ 33 m/ 12 cases/ 1.7 km
Three-minute σ_y, B_{scat}: 227 m/ 95 m/ 11 cases/ 1.7 km
Three-minute σ_y, SO_2: 400 m/ 75 m/ 11 cases/ 6.3 km
Three-minute σ_y, B_{scat}: 389 m/ 49 m/ 11 cases/ 6.3 km
5. σ_z, Cross Section, B_{scat}: 114 m/ 34 min/ 1.7 km
6. σ_z, Spiral, SO_2: 115 m/ 3.1 min/ 6.3 km
σ_z, Spiral, SO_2: 107 m/ 3.4 min/ 6.3 km
σ_z, Sprial, SO_2: 108 m/ 4.0 min/ 6.3 km
σ_z, Spiral, SO_2: 115 m/ 4.8 min/ 6.3 km
σ_z, Spiral, B_{scat}: 117 m/ 3.1 min/ 6.3 km
σ_z, Spiral, B_{scat}: 114 m/ 3.4 min/ 6.3 km
σ_z, Spiral, B_{scat}: 76 m/ 2.4 min/ 6.3 km
σ_z, Spiral, B_{scat}: 134 m/ 4.8 min/ 6.3 km
7. Winds Aloft: NOT AVAILABLE

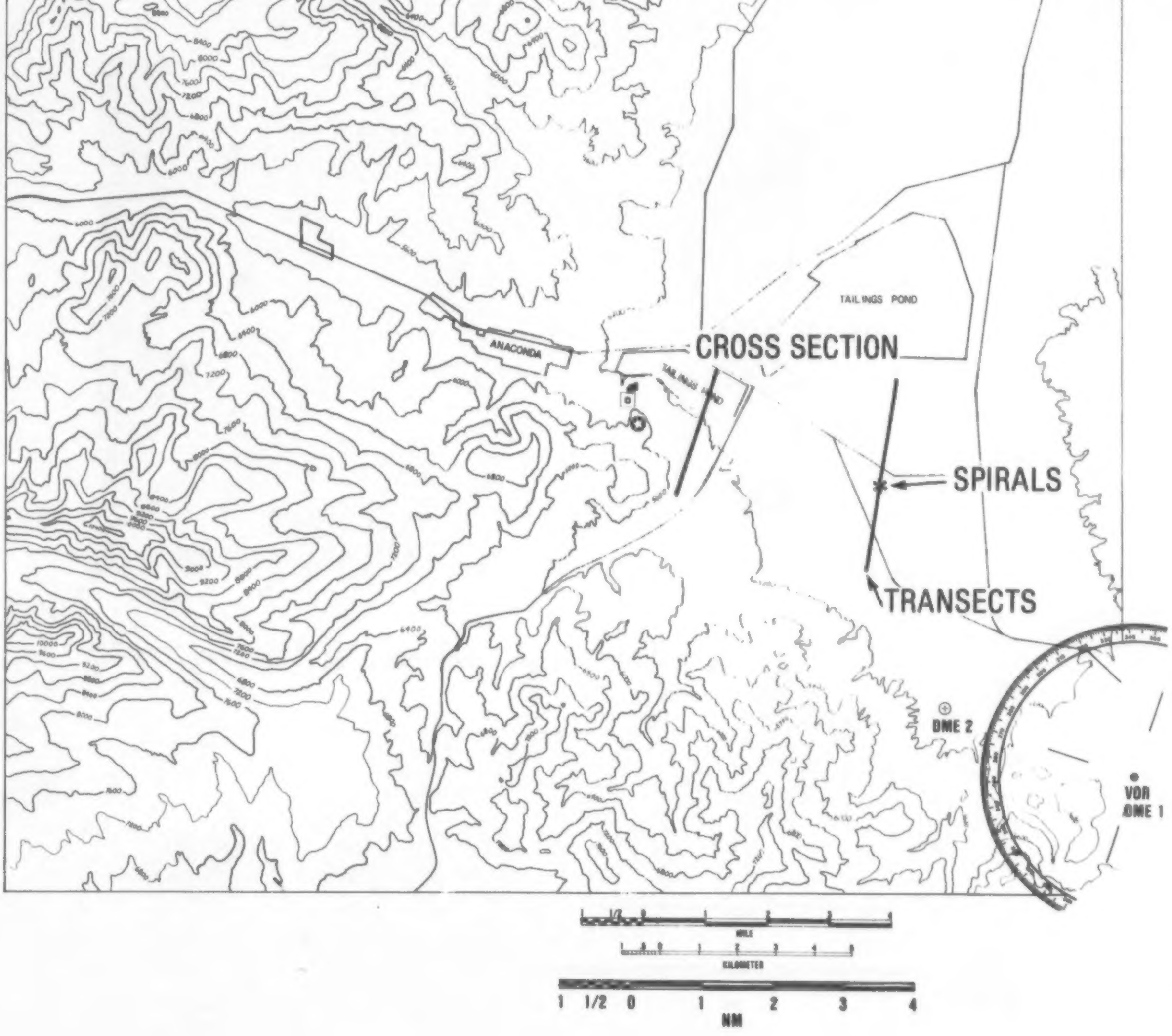

Figure A-117. Sampling Locations, December 3, 1976.

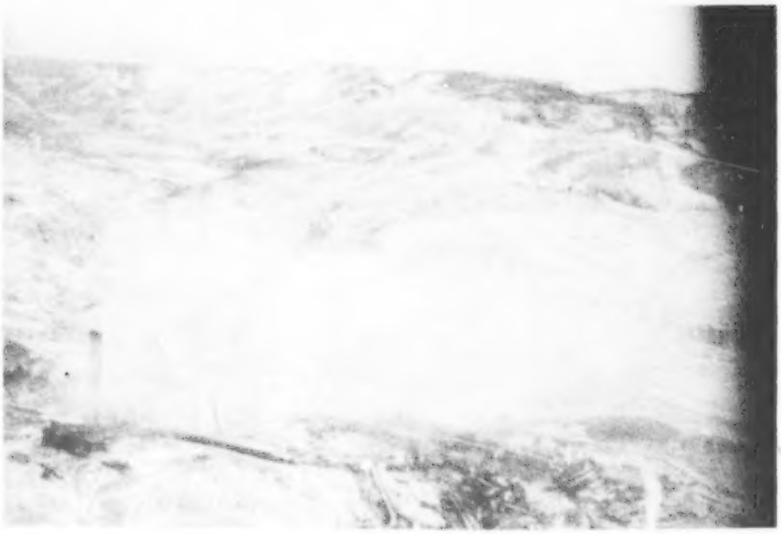

Figure A-118. Plume, December 3, 1976.

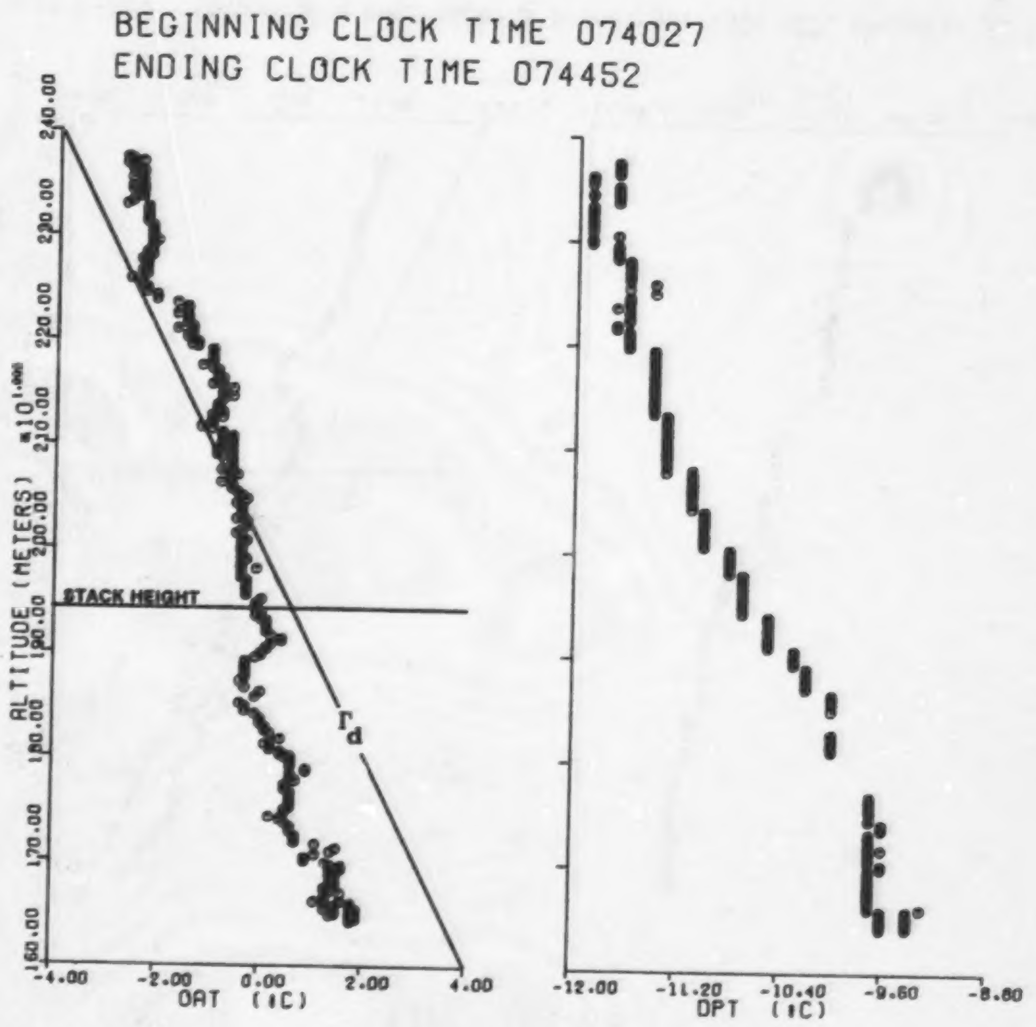

Figure A-119. Temperature and Dewpoint Soundings, 0740 MST, December 3, 1976.

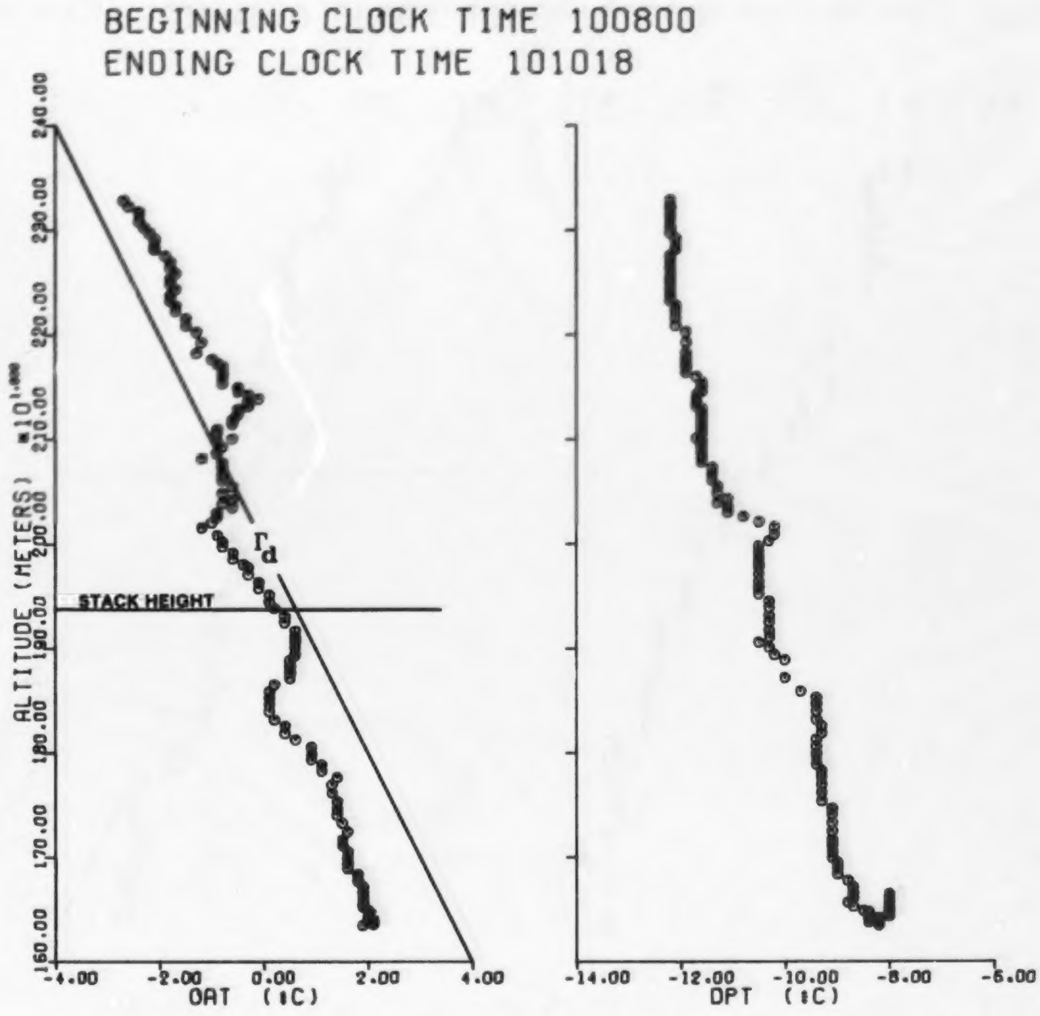

Figure A-120. Temperature and Dewpoint Soundings, 1008 MST, December 3, 1976.

December 8, 1976 0744-0945 MST

Near neutral conditions were initially observed up to approximately 2000 m MSL with stable conditions attributed to subsidence above. By the end of the mission, the layer of subsiding air had built down to near the surface (Figures A-122 and A-123). Strong southwesterly flow was observed throughout the flight. Downwash conditions were noted. Cross sections were attempted at 2.6 km near the area of impaction and at 7.4 km over the portable SO_2 monitor.

TABLE A-33
SUMMARY OF MISSION, DECEMBER 8, 1976

1. Butte Weather: 0750 HI SCT 340/04
   1054 HI SCT 300/03
2. Plant Emissions, SO_2: 0630-0730 20.8×10^9 μg/s
   0730-0830 15.9×10^9 μg/s
   0830-0930 9.9×10^9 μg/s
   0930-1030 9.7×10^9 μg/s
3. Centerline Height/ Distance/ Concentration: 1860 m/2.6 km/ 4.6 ppm
4. Three-minute σ_y, SO_2: 550 m/ 204 m/ 8 cases/ 2.6 km
   Three-minute σ_y, B_{scat}: 461 m/ 90 m/ 5 cases/ 2.6 km
   Three-minute σ_y, SO_2: 674 m/ 174 m/ 18 cases/ 7.4 km
   Three-minute σ_y, B_{scat}: 537 m/ 124 m/ 10 cases/ 7.4 km
5. No determination of σ_z possible.
6. Winds Aloft:

Time (MSL)	Height (m MSL)	Direction (°)	Speed (m/s)
0820	1860	238	15
	1950	241	14

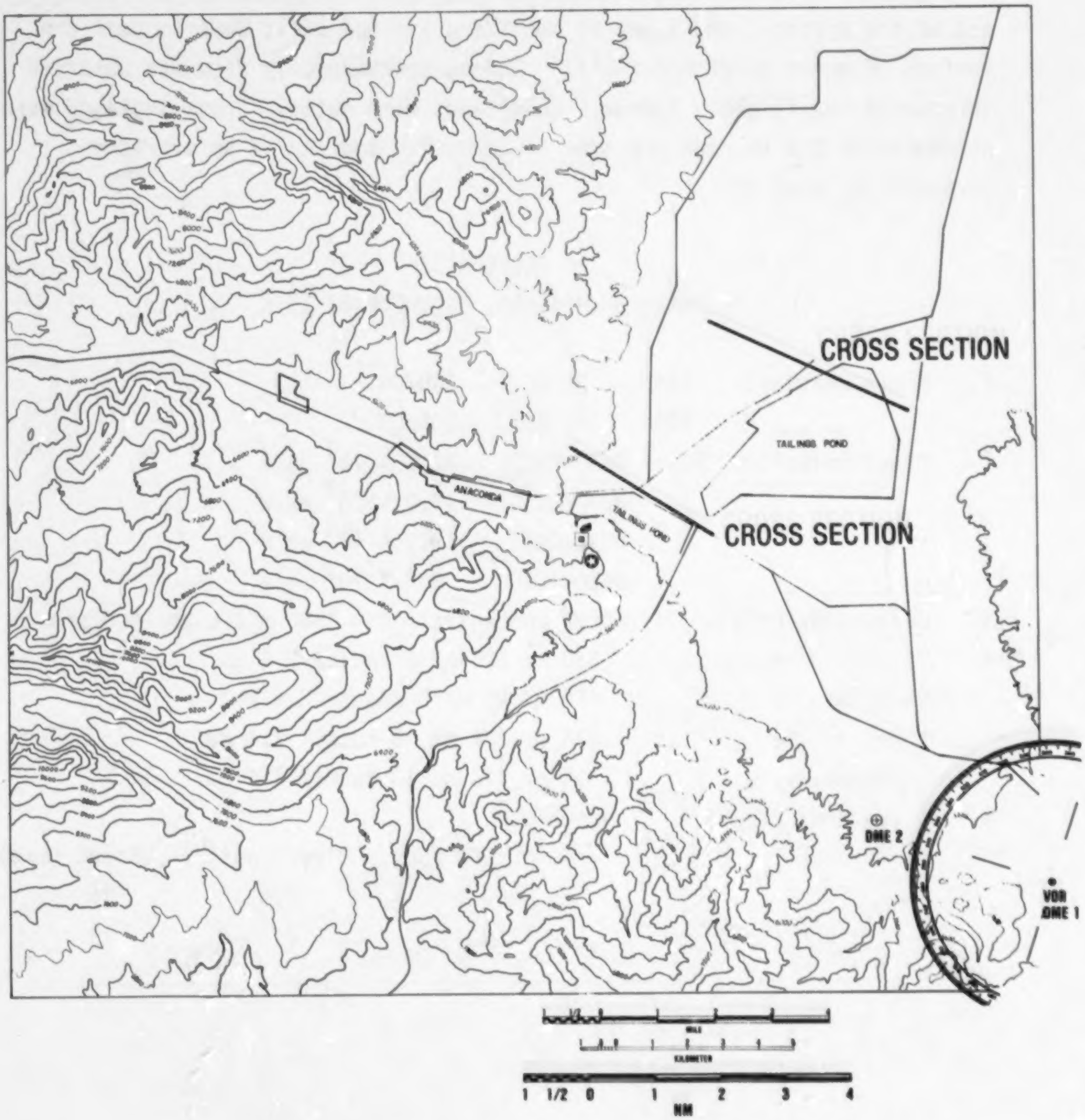

Figure A-121. Sampling Locations, December 8, 1976.

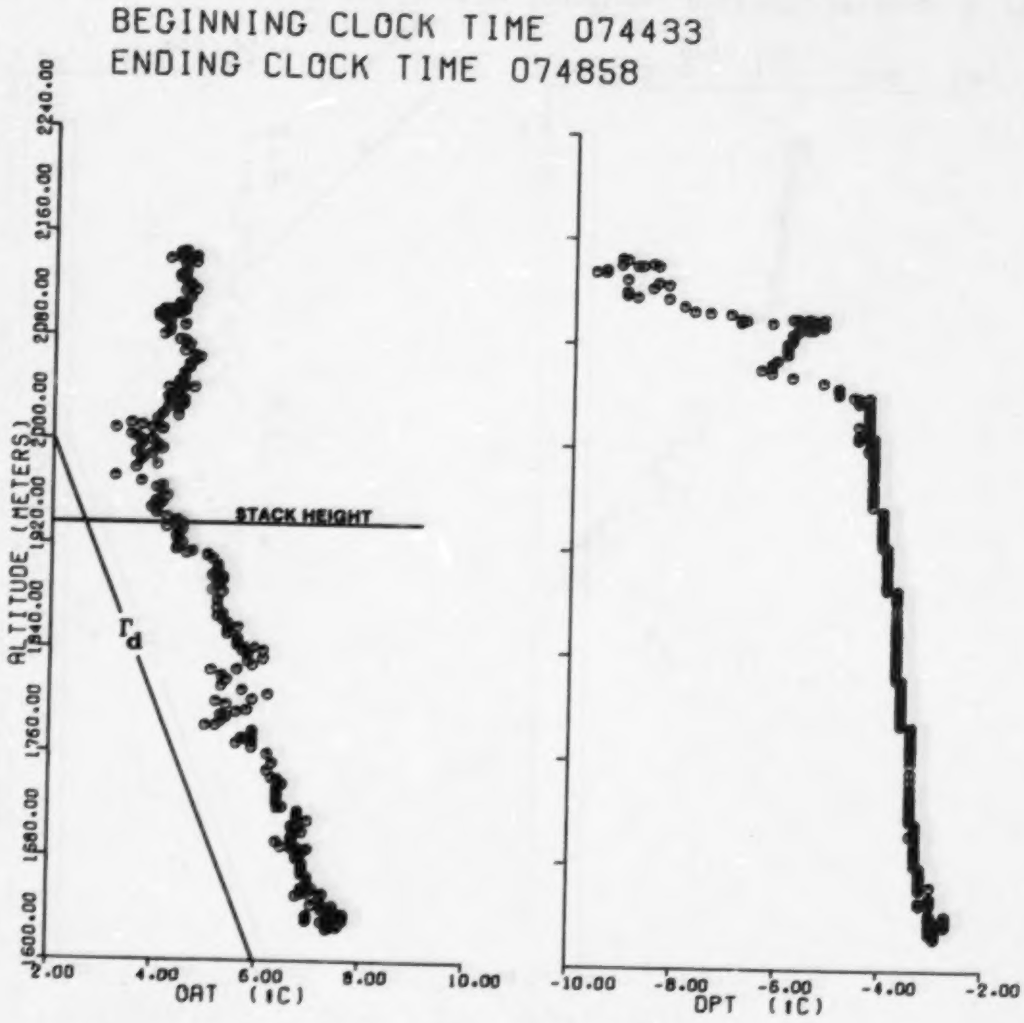

Figure A-122. Temperature and Dewpoint Soundings, 0744 MST, December 8, 1976.

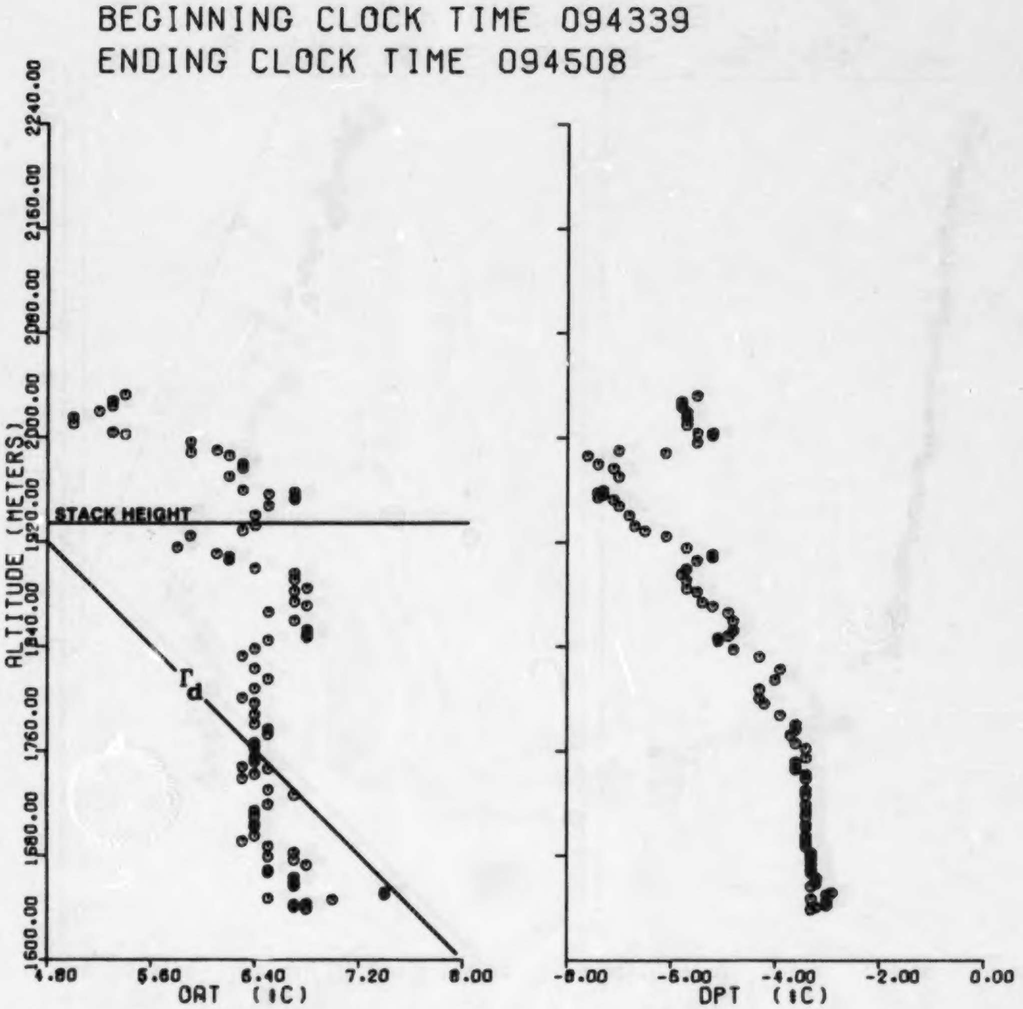

Figure A-123. Temperature and Dewpoint Soundings, 0943 MST, December 8, 1976.

APPENDIX B. DATA ADJUSTMENT

In addition to the routine adjustments that are applied to output data based on pre- and post-flight calibration and pre-, and post- and in-flight zero and span, instrument time response and averaging time were considered when processing these data.

Instrument response adjustments are applied in the following manner: Testing has determined that the nephelometer has a first-order linear response. Figure B-1 is an example of such a response to a step function.

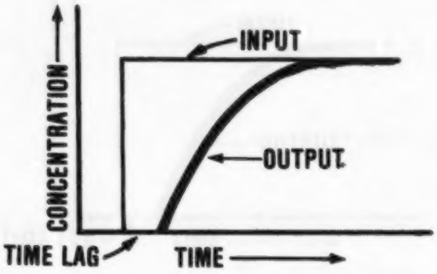

Figure B-1. Example of First-Order Linear Response.

The TECO-43 instrument was tested and was found to have second-order linear response characteristics. Figure B-2 is an example of the response of such an instrument to a step function input.

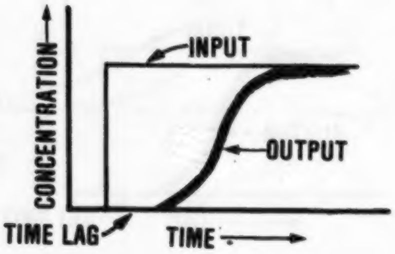

Figure B-2. Example of Second-Order Linear Response.

In general, when neglecting time lag, the relationship between input concentration, x_{in}, and output concentration, x_{out} is:

$$x_{in} = x_{out} + \sum_{i=1}^{\infty} a_i \frac{d^i x_{out}}{dt^i} \quad (1)$$

For a first order system:

$$x_{in} = x_{out} + \tau_1 \frac{dx_{out}}{dt} \quad (2)$$

and for a second-order linear system:

$$x_{in} = x_{out} + (\tau_1 + \tau_2) \frac{dx_{out}}{dt} + \tau_1 \tau_2 \frac{d^2 x_{out}}{dt^2} \quad (3)$$

where τ_1 and τ_2 are time constants.

Figure B-3 is an example of the response that a first-order instrument would have to a Gaussian input.

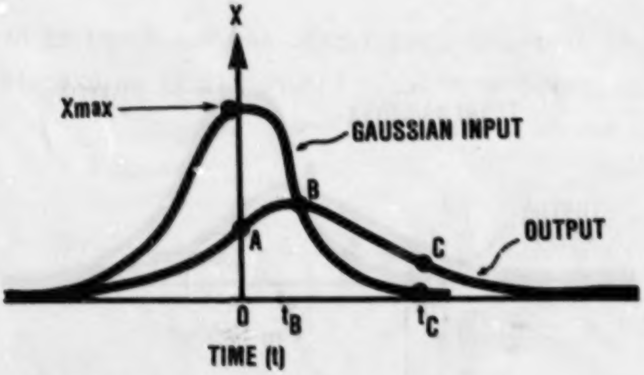

Figure B-3. Response of a First-Order Instrument to a Gaussian Input.

For a Gaussian input,

$$x_{in} = x_{max}\, e^{-t^2/2\sigma^2} \tag{4}$$

and

$$x_{out} = x_o\, e \left[1 + \mathrm{erf}\, \frac{t - \frac{\sigma 2}{\tau 1}}{2\sigma} \right] \tag{5}$$

where

$x_o = f\,(x_{max}, \sigma, \tau_1)$, a constant.

Note: Referring to Figure B-3 for a linear first-order system and a Gaussian input,

A = Inflection point in output corresponding to x_{max},

B = Maximum output value where $x_{out} = x_{in}$, and

C = Exit point from plume. The output is an exponential fall from this point, and from this point onward.

$$x_{out} = x_C\, e^{-(t-t_c)/\tau_1} \quad \text{for } t>t_c. \tag{6}$$

In order to determine input concentrations from output concentrations, we must:

A. Determine τ_1

B. Compute Derivatives, dx_{out}/dt

1. To determine τ_1, we plot in χ_{out} (after subtracting background) vs. time and consider the linear portion of output decay (See Figure B-4).

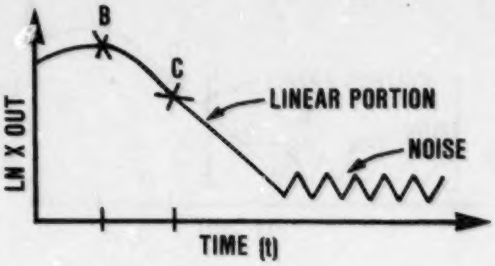

Figure B-4. Example of Exponential Decay for First-Order Linear System.

The slope of the linear portion is equal to $-1/\tau_1$.

An analysis of 99 transects and 17 spirals that were randomly selected and plotted gave the following time constants for the nephelometer (B_{scat}) for each maneuver: $\tau_{spiral} = 3.74s \pm 0.60s$ and $\tau_{transect} = 4.11 \pm 1.43s$.

2. To compute the derivative, $d\chi_{out}/dt$, we note that:

$$\frac{d\chi}{dt} = \chi \frac{d\ln\chi}{dt} \tag{7}$$

and

$$\chi + \tau_1 \frac{d\chi}{dt} = \chi \left(1 + \tau_1 \frac{d\ln\chi}{dt}\right) \tag{8}$$

The expected form of ln χ_{out} from a Gaussian input as shown in equation (5) can be transformed into a polynomial in time by converting exp and erf into their respective infinite series representations.

$$\ln \chi_{out} = \sum_{i=0}^{\infty} b_i \; t \tag{9}$$

where the coefficient b; is a function of σ, τ, and χ_{max}. The numerical differentation technique used is most accurate for polynomial expansions and therefore differentation of lnχ out is expected to be more accurate than differentation of χ out.

Plume parameters are also presented based on SO_2 measurements. The TECO-43 SO_2 monitor was found to have a response that is linear and second order. Therefore,

$$\chi_{in} = \chi_{out} + (\tau_1 + \tau_2)\frac{d\chi_{out}}{dt} + \tau_1\tau_2\frac{d^2\chi_{out}}{dt^2}, \tag{10}$$

and using the log transformation,

$$\chi_{in} = \chi_{out}\left\{1 + (\tau_1 + \tau_2)\frac{d\ln\chi_{out}}{dt} + \tau_1\tau_2\left[\left(\frac{d\ln\chi_{out}}{dt}\right)^2 + \frac{d^2\ln\chi_{out}}{dt^2}\right]\right\} \tag{11}$$

This equation requires knowledge of both the slope and the curvature of the output. The in-flight testing of the instrument accomplished on October 12, 1976, established that $\tau_1 = 1.60s$ and $\tau_2 = 10.5s$. These results were based on 16 tests. It is recognized that the use of the second derivative increases the probably error by a factor of approximately two. The numerical technique used for computer processing of the data to solve the differential equations for χ is the "Method of Milne," (Wylie, 1958). In general terms: $y_i = f(t_i)$ and $t_2 - t_1 = t_3 - t_2 = \Delta t$. For a fit involving N data points, if n is the point at which we want to compute $\frac{dy_n}{dt} = y_n'$

For n=1

$$y_1' = \frac{1}{12\Delta t}(-25y_1 + 48y_2 - 36y_3 + 16y_4 - 3y_5)$$

For n=2

$$y_2' = \frac{1}{12\Delta t}(-3y_1 - 10y_2 + 18y_3 - 6y_4 + y_5)$$

For 2<n<N-1

$$y_n' = \frac{1}{12\Delta t}(y_{n-2} - 8y_{n-1} + 8y_{n-1} - Y_{n+z})$$

For n = N-1

$$y_{n-1}' = \frac{1}{12\Delta t}(-y_{n-4} + 6y_{n-3} - 18y_{n-2} + 10y_{n-1} + 3y_n)$$

For n=N

$$y_n' = \frac{1}{12\Delta t}(3y_{n-4} - 16y_{n-3} + 36y_{n-2} - 48y_{n-1} + 25y_n)$$

APPENDIX C. SAMPLING TIME

The measured peak concentrations downwind from the source increased with a decrease in sampling time because the apparent plume width, as measured for short time periods, was not affected by plume meander. To place centerline concentrations, χ_{max}, onto a common time basis for comparison with other literature tabulations, we have adjusted our values. The maximum concentration for an elevated release with no reflections is $\chi_{max} = Q/2\pi\sigma_y\sigma_z\overline{u}$, where σ_y and σ_z are functions of distance, x, and averaging time, $\overline{t}$, and Q is the emission rate. The rate that χ_{max} decreases with averaging time is assumed to be proportional to t^{-p}, where -p is a constant. If we assume: $\frac{\delta\sigma_y}{\delta t} >> \frac{\delta\sigma_z}{\delta t}$

for stable and neutral cases, then σ_y must increase with averaging time as t^p for short averaging times. Turner (1969) has suggested that p should be between 0.17 and 0.20 for sampling times less than two hours. We have used 0.165 as used by Turner in his workbook example and adjusted the measured values of σ_y to a base time of 3 minutes.

The helicopter traverse measurements correspond more closely to an instantaneous plume (real time measurement) than the time average usually considered.

For example, considering a Gaussian plume and a helicopter air speed of 60 knots (30.9 m/s), the mean sampling time within the plume may be estimated as:

$$\overline{t}\ (s) = \frac{4.64\sigma_y}{2(30.9)} = 0.075\sigma_y\ (s)$$

where 4.64 is the number of standard deviations which contain 98% of the area under the Gaussian curve. Since the Gaussian plume has bilateral symmetry, a flight through half of the plume completely defines its width. A factor of two appears in the denominator to account for the fact that a transect through the plume represents two independent measurements of the half plume. In keeping with the assumption that

$$\frac{\partial\sigma_y}{\partial t} >> \frac{\partial\sigma_z}{\partial t}$$

no adjustments for sampling time have been made for σz. The times given for values of σz represent either the time required to spiral down through the plume or the total time required to construct a cross section of the plume by making a series of transects through the plume at various altitudes.

APPENDIX D. DETERMINATION OF PLUME PARAMETERS

Software was developed to determine plume parameters by application of the method of moments (Pasquill, 19). Given a set of corrected outputs, input = f (time), the area under a curve of concentration vs. time,

$$A = \int \chi_{in} dt \tag{1}$$

$$\bar{t} = \frac{\int \chi_{in}\, t dt}{A} = \frac{\text{First total moment}}{\text{Total area}} \tag{2}$$

The variance of the distribution is:

$$\sigma^2 = \frac{\int \chi_{in}(t-\bar{t})^2 dt}{A} = \frac{\text{Second total moment}}{\text{total area}} \tag{3}$$

or

$$\sigma^2 = \frac{\int \chi_{in}\, t^2 dt}{A} - \bar{t}^2$$

The centerline concentration, χ_{max}, was determined by relation:

$$\chi_{max} = \frac{A}{\sqrt{2}\ \pi\sigma_y} \tag{4}$$

Numerical integration was accomplished by Simpon's rule, (Wylie, 1960).

When reflection either from a stable "lid" aloft or at the surface occurs, it is necessary to make the assumption that we may draw a smooth curve through the adjusted data. We then select equal vertical intervals and input values of height and concentration into our computer program to determine Zo, σ_z^2, χ_{max}, and A. The same technique is used for spirals and cross sections. Graphically, with one reflection at the surface (Figure D-1), we can see the problem as transferring the area under the curve due to surface reflection to a Gaussian curve having equal area and the proper configuration.

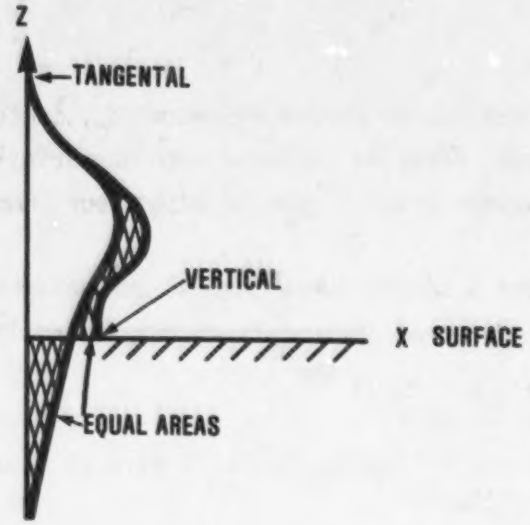

Figure D-1. Example of a Surface Reflection.

Considering the equation for Gaussian distribution, while neglecting the horizontal displacement term,

$$\chi = \frac{Q}{2\pi\bar{u}\sigma_y\sigma_z}\left[e^{-\frac{1}{2}\left(\frac{Z-H}{\sigma_z}\right)^2} + e^{-\frac{1}{2}\left(\frac{Z+H}{\sigma_z}\right)^2}\right] \tag{5}$$

We may write:

$$\chi = \frac{Q}{2\pi\bar{u}\sigma_y\sigma_z}\; e^{-\frac{1}{2}\left(\frac{Z-H}{\sigma_z}\right)^2}\left[1+\frac{e^{-\frac{1}{2}\left(\frac{Z+H}{\sigma_z}\right)^2}}{e^{-\frac{1}{2}\left(\frac{Z-H}{\sigma_z}\right)^2}}\right] \tag{6}$$

and

$$\chi = \frac{Q}{2\pi\bar{u}\sigma_y\sigma_z}\left(1 + e^{\frac{2HZ}{\sigma_z^2}}\right)e^{-\frac{1}{2}\left(\frac{Z-H}{\sigma_z}\right)^2} \tag{7}$$

We may now replot as normal distribution, χ'

$$\chi' = \frac{\chi}{1+e^{-2HZ/\sigma_z^2}} = \frac{Qe^{-\frac{1}{2}\left(\frac{Z-H}{\sigma_z}\right)^2}}{2\pi u\sigma_y\sigma_z} \tag{8}$$

In order to replot, we choose values of Z_o, centerline height, and σ_z that will give equal areas as compared with our original adjusted output curve.

The complete process used to adjust our plume with a reflection is as follows:

1. Draw a smooth curve through our adjusted data.
2. Choose equal intervals of height and input to our computer program to obtain Z_o, σ_z^2, χ_{max}, and A.
3. Replot data.
4. Assume Z_o and σ_z that will give us a Gaussian plume having the same area as our plume in step 3.
5. Choose values of χ' and Z and input to our computer program to obtain Z_o and σ_z. If Z_o and σ_z are similar to step 4, stop. If not, repeat step 4.

Plume parameters are once again determined by the method of moments. A second method of determining χ_{max} for SO_2 is to assume that the SO_2 and B_{scat} plumes have identical shapes. Then if A_{SO_2} and $A_{B_{scat}}$ are the respective areas under the output curves of SO_2 and B_{scat}:

$$\frac{A_{SO_2}}{\chi_{max\ SO_2}} = \frac{A_{B_{scat}}}{\chi_{max}{}_{B_{scat}}} \tag{12}$$

or

$$\chi_{max\ SO_2} = \frac{A_{SO_2}\ \chi_{max}{}_{B_{scat}}}{A_{B_{scat}}} \tag{13}$$

APPENDIX E. DISCUSSION OF DATA

The following statistical analysis has been made in order to test the validity of our data: In the absence of loss of SO_2 by scavenging or chemical transformation, the maximum SO_2 concentration, χ, at the plume centerline is:

$$\chi = \frac{Q}{2\pi\sigma_y\sigma_z u} \qquad (1)$$

where:

χ = centerline concentration ($\mu g/m^3$)
Q = emission rate ($\mu g/s$)
σ_y = horizontal dispersion coefficient (m)
σ_z = vertical dispersion coefficient (m)
u = wind speed (m/s).

The equation can be written as:

$$R = \frac{2\pi\chi\sigma_y\sigma_z u}{Q} \qquad (2)$$

where R is the ratio of measured emission to estimated emission when χ, σ_y, σ_z, u, and Q are accurate and have random measurement errors, the measurements should scatter about unity. On 17 occasions, all of the parameters were available to determine R. Values of R are tabulated and presented in Table E-1.

The following statistics have been calculated:
the mean of R, $\overline{R} = 2.11$
the standard deviation of R, $\sigma_R = 2.35$
the geometric mean of R, $\overline{GR} = 1.87$
the geometric standard deviation of R, $\sigma_{GR} = 1.92$.

TABLE E-1
VALUES OF R

Rank	Ratio (R)
1	0.70
2	0.92
3	1.13
4	1.20
5	1.24
6	1.46
7	1.60
8	1.72
9	1.88
10	1.89
11	2.30
12	2.30
13	2.93
14	3.46
15	3.46
16	3.63
17	4.05

Since the five parameters of equation (1) are independent, the values of R may be lognormally distributed. A test for lognormality is the Kolmogorov-Smirnov (KS) Test. Plotting the values of R on log probability paper at frequencies, f = rank/N + 1, where N is the total number of samples, 17, the data are fit by a lognormal distribution with the experimental geometric mean, $\overline{GR}$, and the standard deviation, σ_{GR} (Figure E-1). The maximum deviation in terms of frequency between the data and the line is 0.06 (0.945 - 0.885) which is the KS statistic. As can be seen from Table E-2 of KS statistics, the statistics are significant at a level much higher than 20% and the distribution cannot be rejected as a fit.

The geometric mean of 1.87, as opposed to 1.00, indicates that there may be a large bias in one of the five measurements. Since the ratio R is the product of five measurements, the geometric standard deviation should be the square root of the sum of the squares of the standard deviation of the five measured quantities.

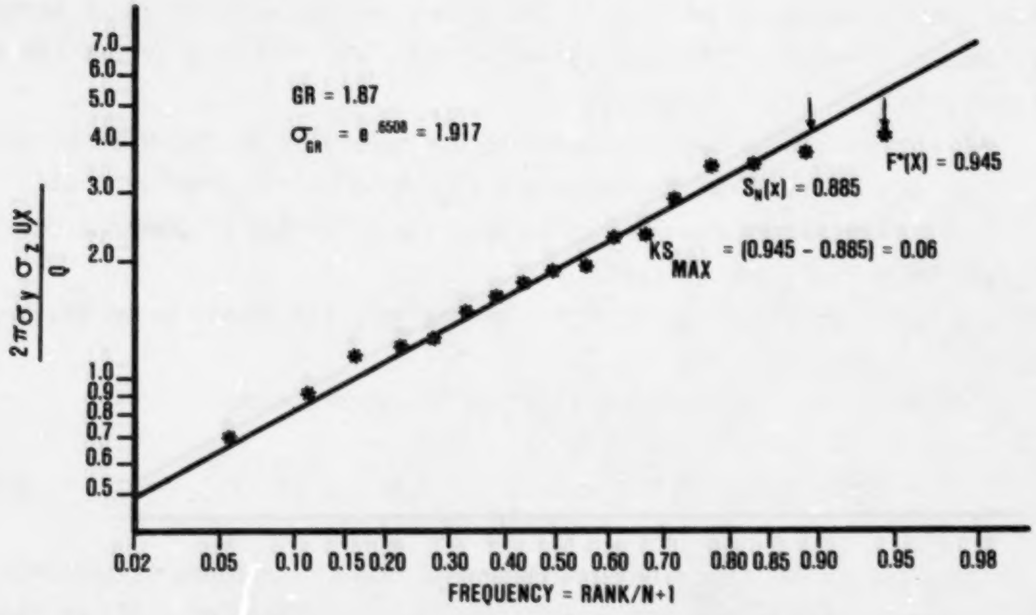

Figure E-1. Equation (1) vs. Frequency.

TABLE E-2

TABLE OF CRITICAL VALUES OF KS

Sample Size N	Level of Significance in KS = $\lvert F^*(\chi) - S_N(\chi) \rvert$				
	0.20	0.15	0.10	0.05	0.01
	0.169	0.177	0.189	0.200	0.235

*The values of KS given in the table are critical values associated with selected values of KS. Any value of KS which is greater than or equal to the tabulated value is significant at the indicated level of significance. These values were obtained as a result of Monte Carlo calculations, using 1000 or more samples for each value of KS. $F^*(\chi)$ is the model value and $S_N(\chi)$ is the observed value.

If there were no errors in any of the measurements, the geometric standard deviation would be 1.0. The difference between the actual standard deviation and 1.0 gives the total error in the measured quantities and equals the square root of the sum of the squares of the individual errors. Of the five quantities making up R, only the errors for the emission rates cannot be estimated. However, these may be calculated. The following errors are estimated for the other parameters:

u is measured by double theodolite and should be on the order of ±20%.

σ_y is measured from transects and should be on the order of ±20%.

σ_z is determined from a complex analysis of spiral or transect data and should be on the order of ±35%.

χ is determined by another complex analysis and should be on the order of ±35%.

If we assign the remaining error to Q scatter, then

$$\sigma^2 = (0.917)^2 - (0.2)^2 - (0.2)^2 - (0.35)^2 - (0.35)^2, \text{ or } \sigma_Q = 0.72.$$

The apparent lognormal distribution of these data tends to indicate that the experiemental errors are random. The geometric mean of 1.87, as opposed to 1.00, indicates that there may be a large bias in one of the five measurements. The parameters χ, σ_y, σ_z, and u are estimated to have a precision on the order of 25%. The analysis of the raw data which produces these parameters would underpredict and overpredict equally often and therefore would not cause a significant bias of the geometric mean of R from 1.00. The emissions, Q, could have a bias since they are estimated for an hourly period and large upward excursions for shorter periods are possible during periods of charging or blowing. Although the analysis shows an unexpectedly large deviation from unity, the lognormality of these data indicate that the estimated uncertainties of ± 25% for the plume parameters are not unreasonable.

An inspection of the vertical and horizontal dispersion coefficients (Figures E-2, E-3, and E-4) obtained from helicopter measurements immediately points out two facts: the rapid dilution near the source (The Pasquill-Gifford curves are included for comparison) and the large amount of scatter of the data. The large amount of scatter points out the problem of calculating dispersion in complex terrain. An attempt has been made to stratify these data by categorizing the data to various parameters. The first involved identifying the coefficients as to atmospheric stability near stack height from helicopter-obtained soundings (Figures E-2, E-3, and E-4). Both measurements from the nephelometer and SO_2 instrument are included. It is evident that due to the complexity of the terrain such a stratification had little meaning. In fact, the average rate of horizontal diffusion associated with stable conditions was more rapid than for the neutral cases. An attempt to stratify the data by wind speed was unsuccessful as was the height-of-plume rise.

We next investigated the physical processes that produced thermal stability. To facilitate data processing, the average σ_y and σ_z values obtained from the two instruments, if both were operational, were used in subsequent analyses. In addition, the average σ_z values at a given distance for a given mission were used.

Three types of thermally stable conditions were identified. The first was a result of the fact that the smelter is on the eastern slope of the continental divide. Westerly flow (a preferred direction) frequently results in the formation of a subsidence inversion at stack height. The flight of October 7, 1976 is one of the many examples of this type of flow. The second and rather rare type is associated with a strong nocturnal inversion coupled

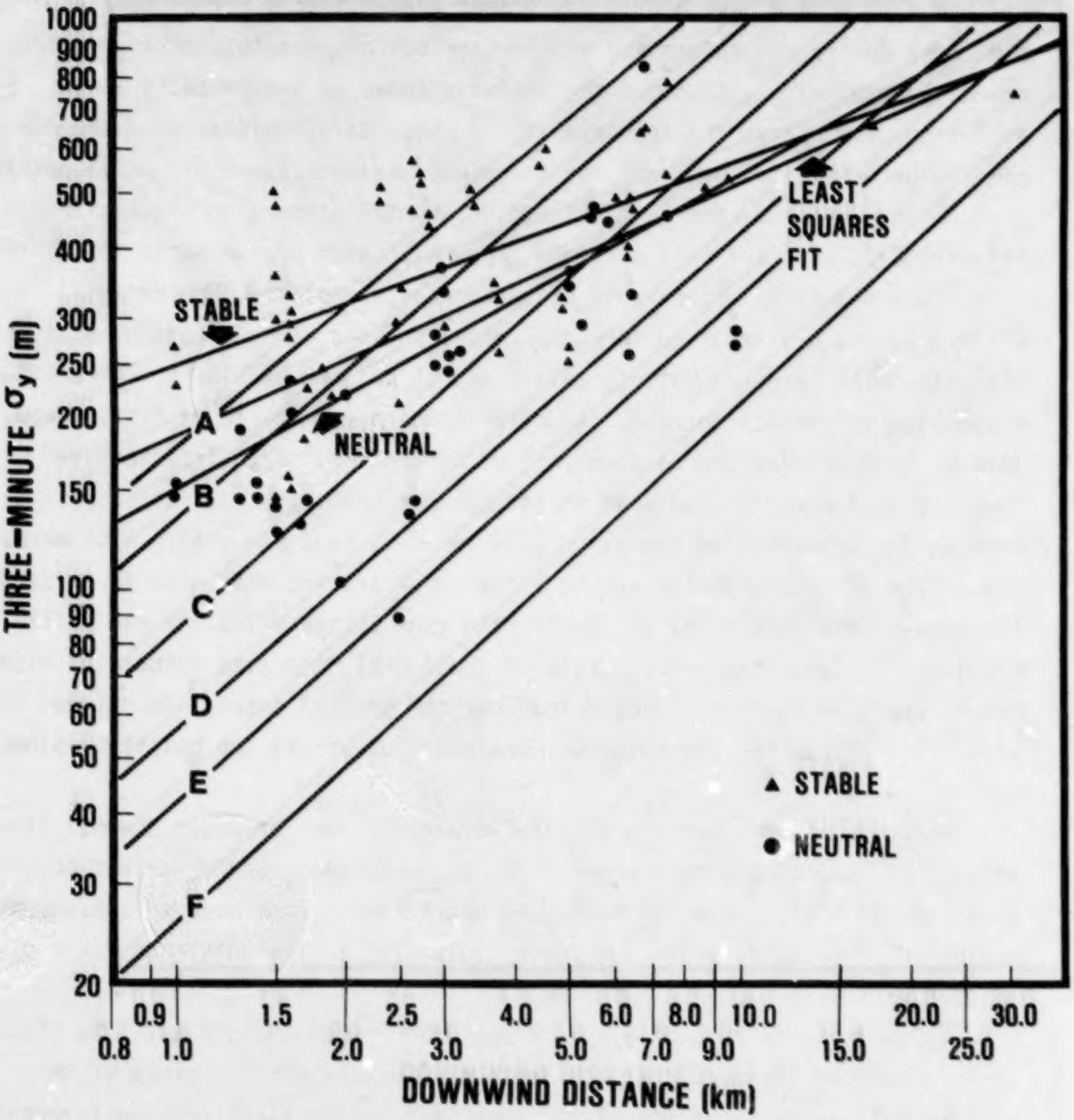

Figure E-2 Horizontal Dispersion Coefficients vs. Downwind Distance.

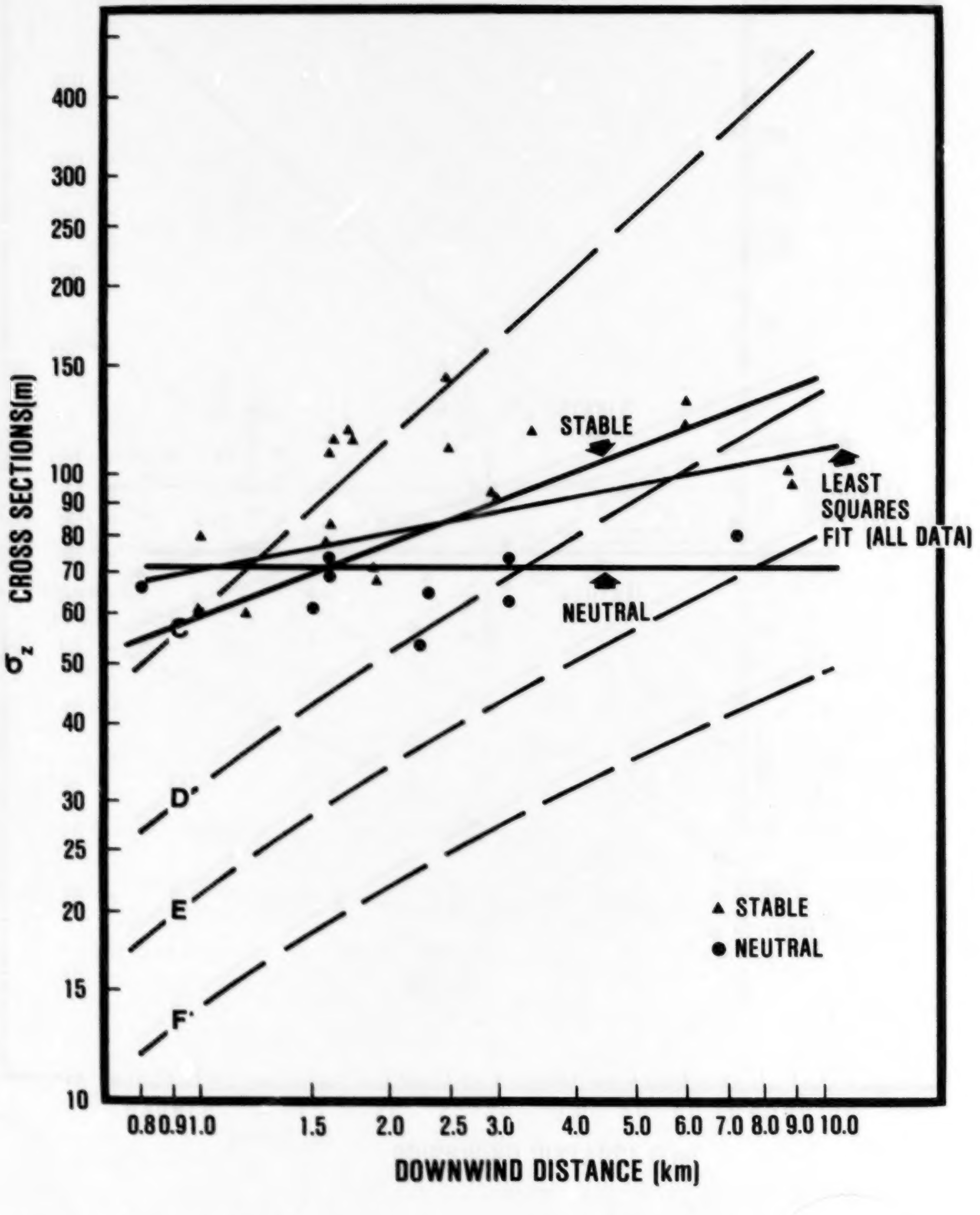

Figure E-3. Vertical Dispersion Coefficients Determined from Cross Sections vs. Downwind Distance.

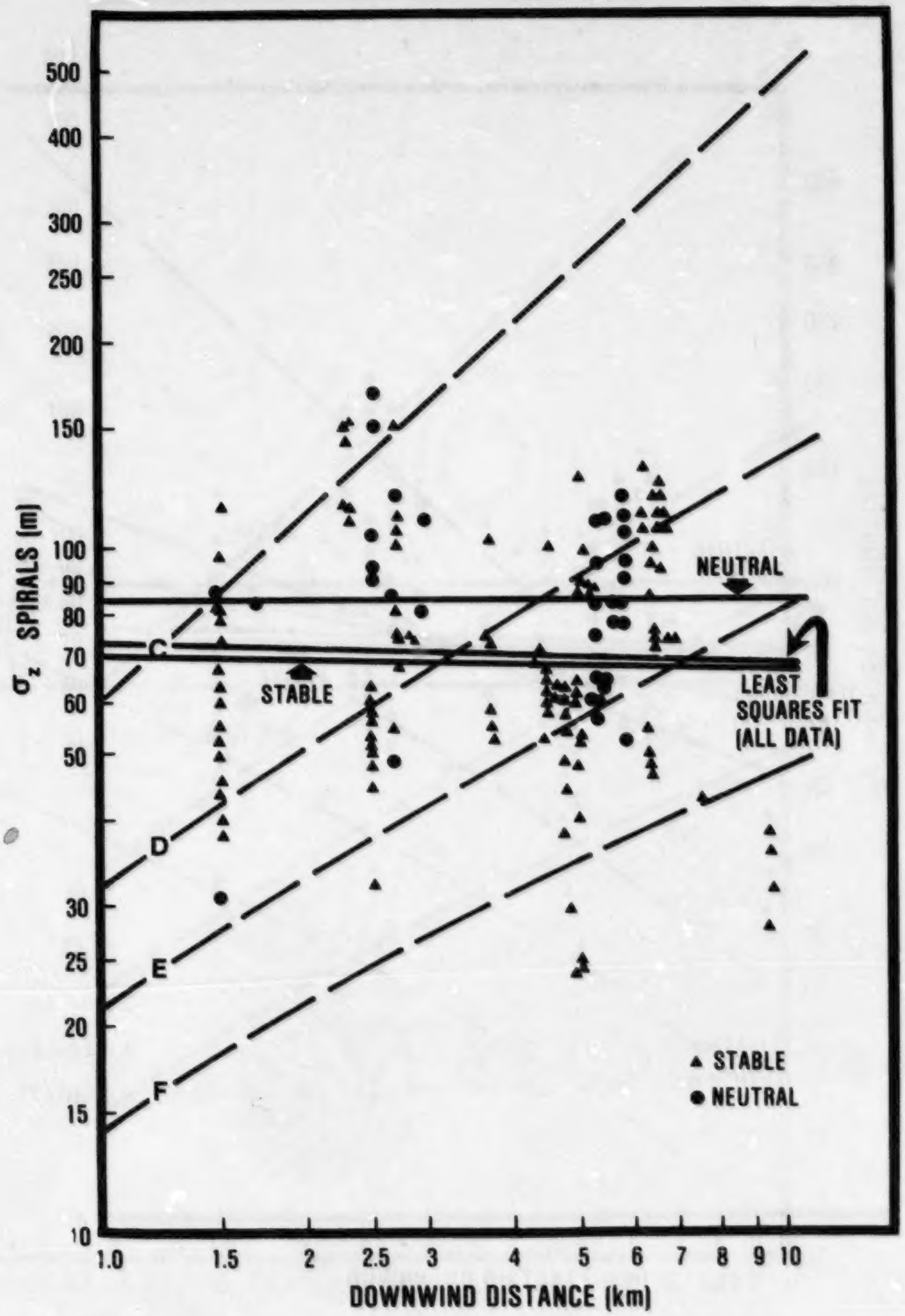

Figure E-4. Vertical Dispersion Coefficients.

with nearly calm winds. In this type of stable condition, large dispersion coefficients are generated as the plume slowly meanders over a large area as little downwind advection occurs. The observations taken at 1.5 km on November 8, 1976 are an example of this case. The third stable type is the classical radiation inversion with associated weak flow. Observations taken on November 11 and 12 are examples of this type of inversion. Due to the fact that over half of the sampling days had westerly winds, the data was broken into two categories, the first being flow from the mountainous area to the west of the stack and the second being all other flow. This attempt was somewhat productive in that stratification of the σ_z data was obtained (Figures E-5, and E-6). However, the stratification of σ_y values was less than satisfactory (Figure E-7).

Next, the σ_y values associated with westerly flow were broken down as to those cases where a subsidence inversion, as determined by temperature and dewpoint data, was present at plume height and those cases where no such inversion was present. A marked stratification of σ_y data was now achieved. The average case where a subsidence inversion was formed due to katabatic flow from the Mount Hagen area exhibited diffusion rates measurably greater than the averages of the other two cases.

Figure E-8 is a graphical presentation of the complexity of the topography in the immediate vicinity of the smelter. It is apparent that flow from any of the octants will result in adiabatic expansion or compression over hundreds of meters and a resultant departure from stability classification estimates based on insolation, cloud cover, and wind speed. In addition, even a casual inspection of the undulatory nature of the terrain will result in an appreciation of the complexity of flow patterns in the vicinity of the smelter. It is noted that westerly flow should result in a katabatic flow.

In addition, other nonturbulent processes associated with airflow patterns in complex terrain which produce divergence and stretching play an important role in plume dispersion (Fosberg, et al. 1976). These cannot be calculated with our limited wind data. The effects of wake turbulence in the lee of this stack having an 18.3 m diameter also would enhance initial dilution.

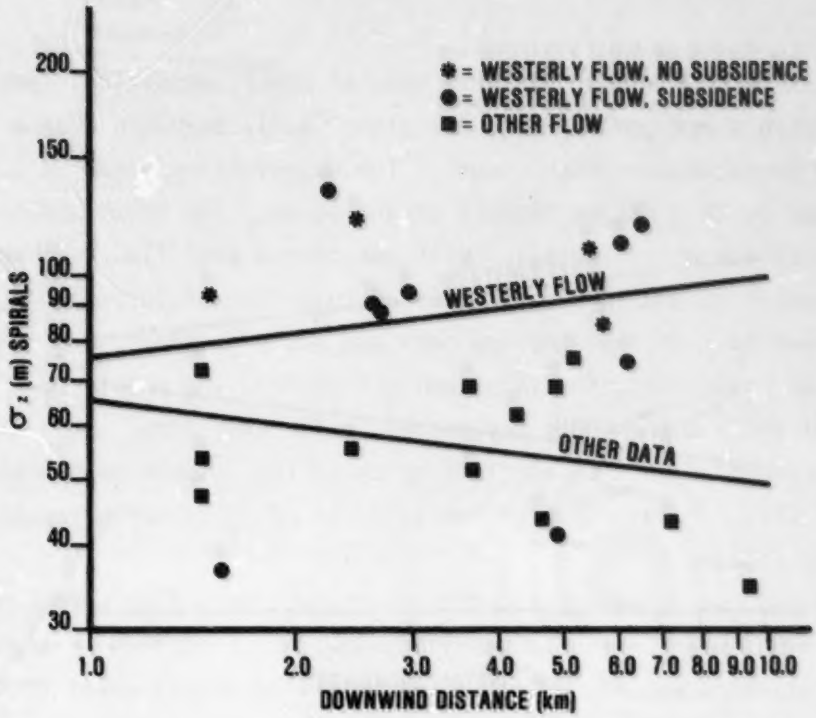

Figure E-5. σ_z Values Stratified by Wind Direction, Spirals.

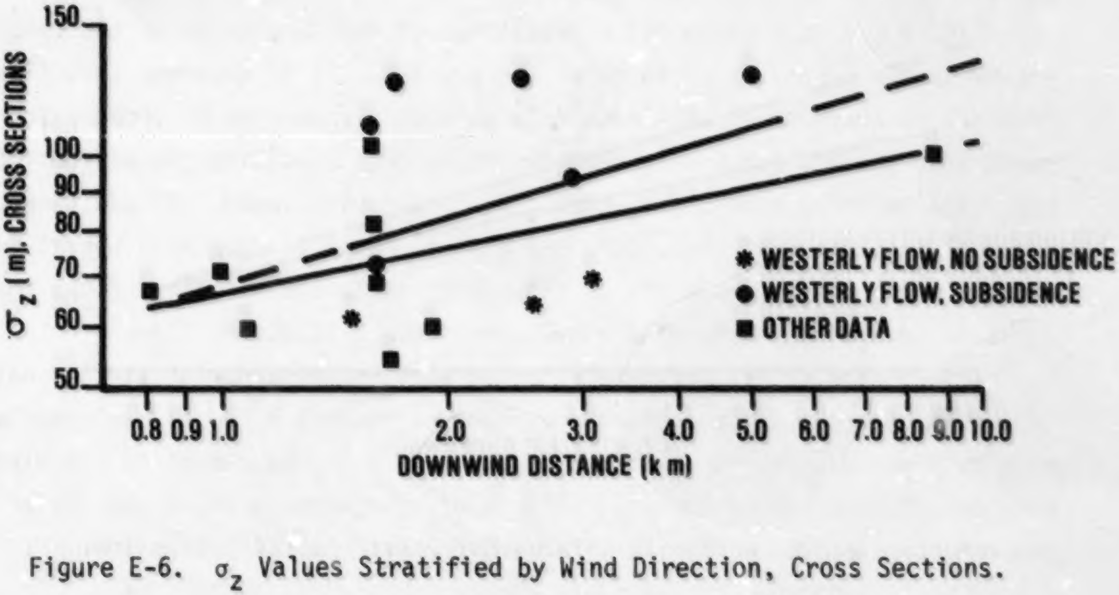

Figure E-6. σ_z Values Stratified by Wind Direction, Cross Sections.

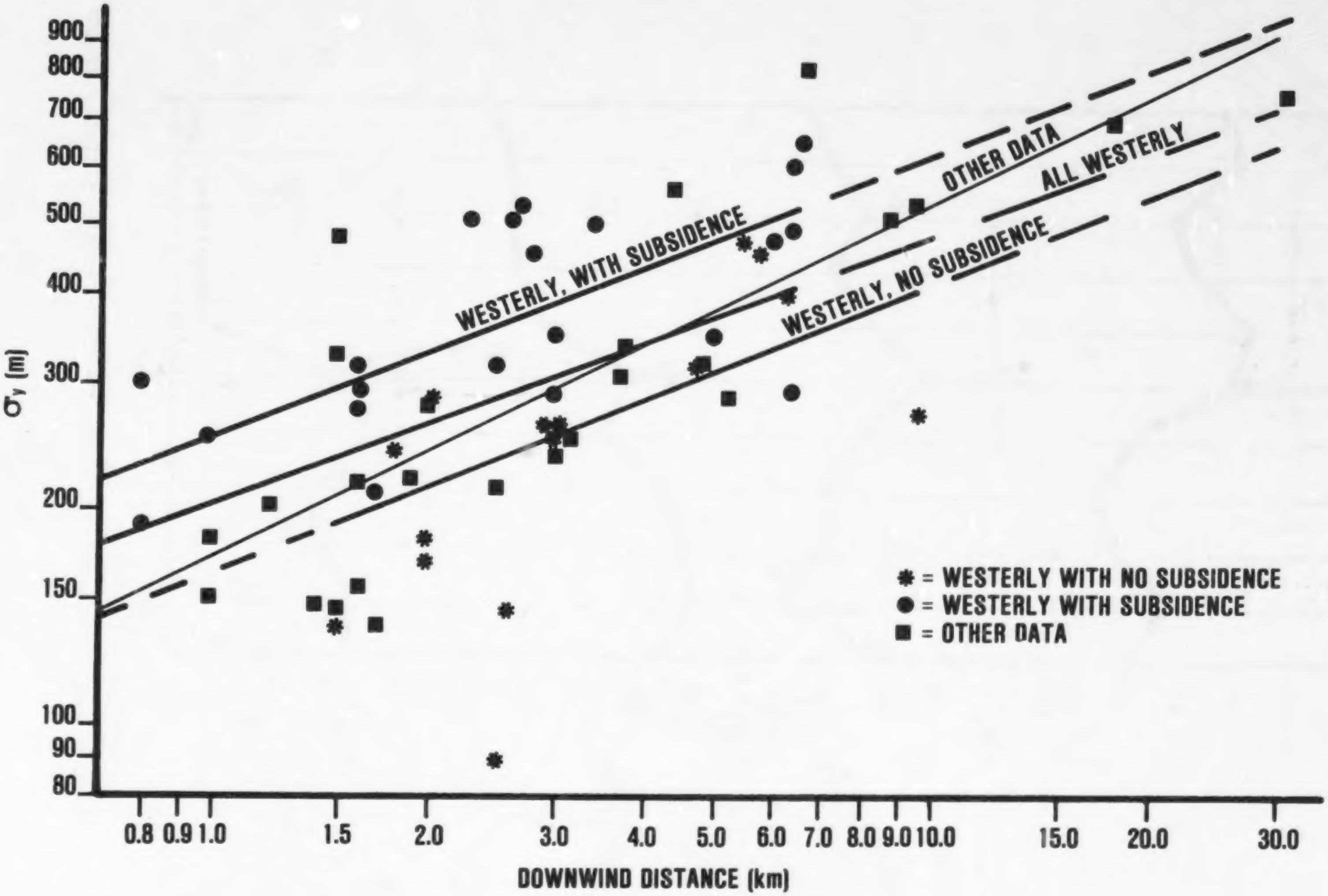

Figure E-7. σ_y Values Stratified by Wind Direction.

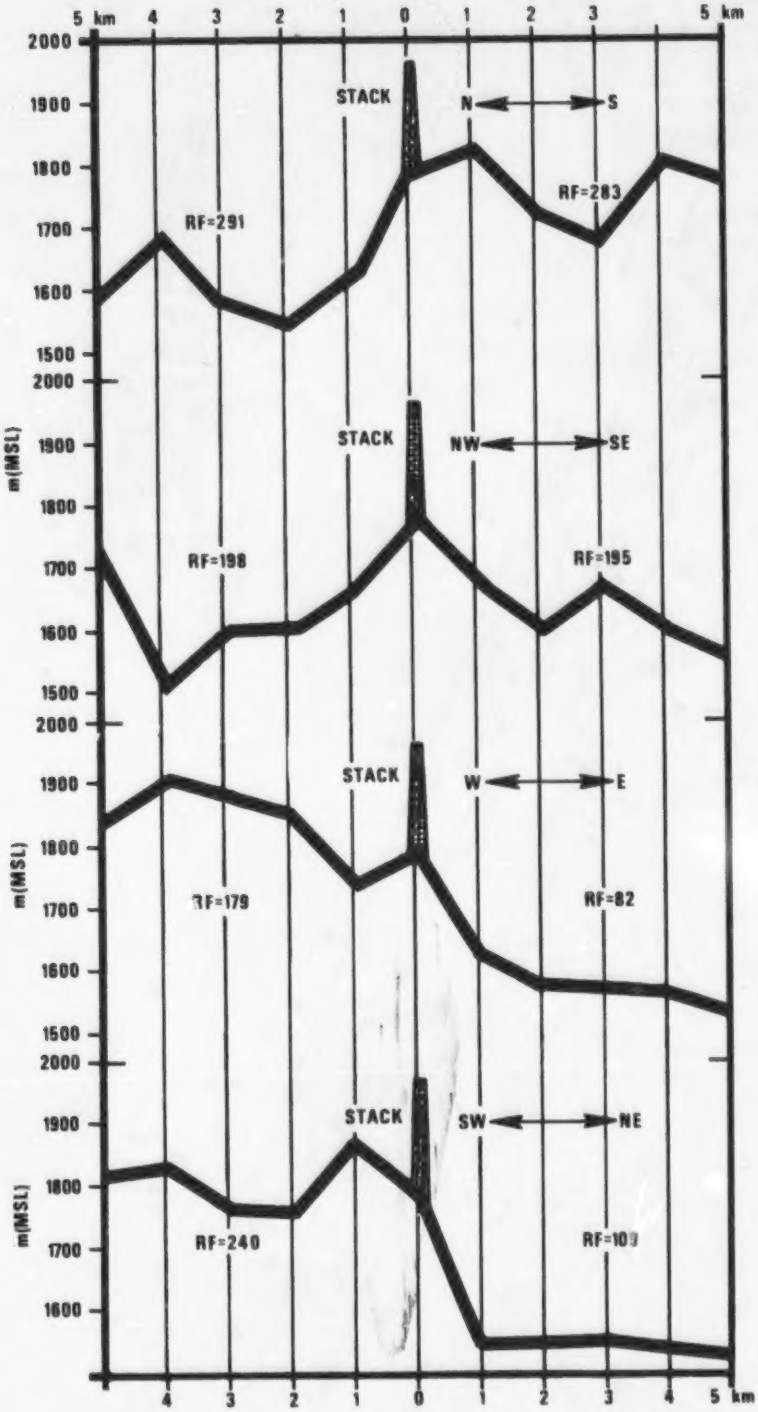

Figure E-8. Topographical Cross Sections in the Vicinity of the Stack.

The effects of increased surface roughness and the associated increase in the rate of diffusion have been observed by McElroy and Pooler (1968) and Start, et al. (1975), and calculated by Liu and Durran (1977). The tendency for more rapid dilution in complex terrain than predicted by Turner for flat terrain has been reported by Bowne (1974) and Whaley and Lee (1977).

APPENDIX F. UPPER LEVEL WINDS

Double theodolite wind observations were, in general, made at 30-minute intervals during the times when the helicopter was sampling. Figure F-1 shows the approximate location of the three pibal pads. Pad A was used on a routine basis. The location of the second pad was determined by wind direction, i.e., the base line was selected that would be as perpendicular to the flow as possible. The distance AB = 344.34 m and AC = 402.84 m. The orientation of base line AB was 268.15° and AC, 31.15°. These directions were based on sightings of the north star. The data have been processed on a CDC-6400 computer using a program written by NOAA personnel assigned to ERDA-Las Vegas, Nevada, using a method by Thyer (1962). In this report, winds are given for each flight for 1950 m, the stack height is 1934 m, and near the height of the plume centerline. A complete set of wind data is on file at this office.

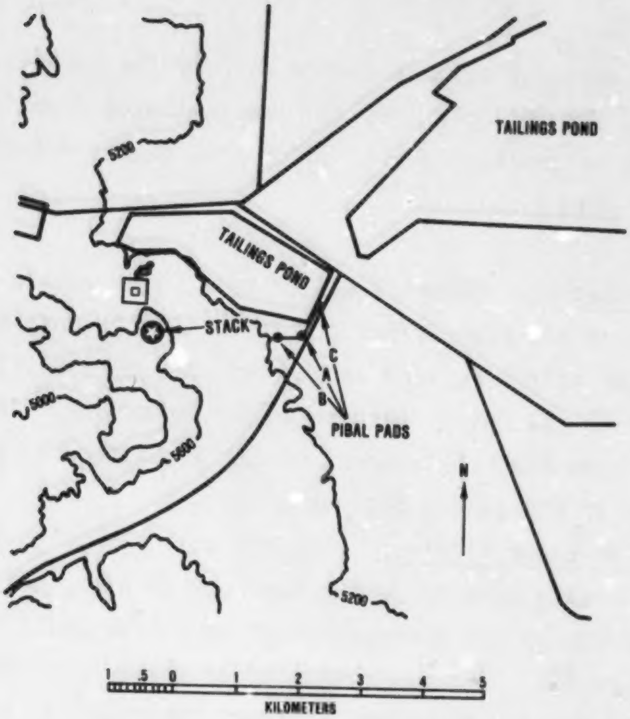

Figure F-1. Location of Pibal Pads.

APPENDIX G. PLANT EMISSION ESTIMATES

Hourly emission estimates were made by the Technical Support Section of Region VIII, EPA (O'Boyle, 1977). The following formula was used in making these estimates: Total sulfur = Roasting + Convertor + Base emissions - Acid plant.

1. Roasting: (lbs/hr) was calculated by multiplying the tons of roaster charge per hour (t/hr) read from the Anaconda operating records by the pounds of sulfur emitted per ton of charge (lbs S/t chg), which was estimated from the daily roasting sulfur emissions. These in turn were calculated from Anaconda records of daily roaster charge tonnage of sulfur in the roaster charge and product (calcines).

2. Convertor Blowing: (lbs/hr) was calculated by multiplying the connector blowing minutes during the hour (min/hr) which was obtained from company records by the average pounds of sulfur emitted per convertor blowing minute (lbs/min). This was estimated by describing the total sulfur in the matte for the period November 1 through November 17, 1976, by the total convertor blowing minutes during that period.

3. Base Emissions: The sum of average hourly sulfur emission rates was obtained by interpolating plots of daily electric furnace emissions and 4-day running averages of daily estimates of the reverberating furnace emissions. These estimates were made from reverberating and roaster charge weights and the analyses of these charges, calcines, and mattes for sulfur.

4. Acid Plant: The intake of the acid plant (120 lbs/hr) was calculated by multiplying the acid plant operating minutes during an hour by the pounds of sulfur intake by operating minute. This constant was calculated from plant operating data for October, November, and December 1976 and February 1977.

The results of these calculations of sulfur emissions were then used to calculate SO_2 emissions in $\mu g/m^3$ to make them compatible with other parameters.

APPENDIX H. COMPUTATION OF STABILITY CLASSIFICATIONS

If one desires to compare the reported values of σ_y and σ_z with the values associated with the various stability categories as suggested by Turner (1969), Butte surface weather is provided in the description of each flight. An estimate of surface wind speeds may be obtained from the pibal wind data. To further assist in the determination of stability classification, the following information concerning insolation has been obtained from the Smithsonian Tables for Anaconda, Montana (Table H-1).

TABLE H-1
TIMES OF DAYLIGHT AND SOLAR ELEVATION

Daylight (1 hour after sunrise)

October 1, 1976, 0636 True Solar Time (TST)
November 1, 1976, 0721 TST
December 1, 1976, 0756 TST

Solar Elevation

October 1, 1976, 32° at 0938 TST
November 1, 1976, 19° at 0944 TST
December 1, 1976, 15° at 0924 TST

Table H-2 presents Turner's stability categories in six classes. Class A is the most unstable class, while class F is the most stable. Night extends to one hour after sunrise. The neutral class can be assumed for overcast conditions for night or day. Slight insolation corresponds to solar elevations from 15° to 35°.

TABLE H-2
KEY TO STABILITY CATEGORIES*

Surface Wind Speed (m/s)	Day Incoming Solar Radiation Strong	Day Incoming Solar Radiation Moderate	Day Incoming Solar Radiation Slight	Night Thin OVC or $\geq$4/8 Low	Night $\leq$3/8 Cloud
<2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	C-D	C	D	E
5-6	C	D	D	D	D
>6	C	D	D	D	D

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*See page 206 for explanation of classifications.

APPENDIX I. COMPARISON OF σ_z FROM SO_2 AND B_{SCAT}

The question may arise as to the validity of using the nephelometer to measure diffusion in the vertical. One might expect that the settling of velocity of particles having a size near the wavelength of light might be such to influence the results obtained from the use of this instrument. A comparison of all of the coincident values of σ_z obtained from analysis of SO_2 data and the B_{scat} data for distances between 1.5 and 6.4 km from the stack gives the following results: $\bar{\sigma}_y\ (B_{scat}) = 69$ m, $\bar{\sigma}_y\ (SO_2) = 70$ m. From this one must conclude that little fallout of aerosols occurs between these distances and the use of the nephelometer is justified.

APPENDIX J. QUALITY ASSURANCE PROCEDURES

Calibration for the Sikorsky-58 helicopter instruments was organized to ensure valid data with a minimum of loss. Zero and span gas calibrations were performed before and after each mission. In addition, zero air readings were taken during the course of each flight. These were combined to determine instrument drift during the sampling period. This information was used to determine the adjustment due to drift at any specific instance during the flight.

The span gases used to calibrate the REM ozone and Andros carbon monoxide instruments were diluted through a Bendix Dynamic Calibration System. The source of zero grade dilution air was the Aadco pure air generator. Span gas used to calibrate the Teco SO_2 instrument was fed directly into the intake port of the instrument. The MRI nephelometer was calibrated with Freon gas as prescribed by the manufacturer. The Cambridge temperature/dewpoint monitor was calibrated using precision resistors.

The span gases (Scott-Marrin SO_2 mixtures in aluminum cylinders) that were used in the calibration of the SO_2 instrument were tested for concentration by the wet pararosanailine method presented by the Federal Register, 40 CFR, Part 50, Part 53, Subposts A, B, and C, Volume 38, No. 197, October 12, 1973. All calibrations were conducted by contract personnel of the Lockheed Electronics Corportation.

Table J-1 presents the results of titrations made to determine cylinder concentrations.

TABLE J-1
SULFUR DIOXIDE CYLINDER HISTORIES

1. Scott Marrin (SM), SO_2 Cylinder #11394, Used October 1 - 12, 1976:

Date of Analysis	SM Value	LEC* Value	% Difference	% Precision
04/20/77	98.3 ppm	97.67**	-0.64	1.78 (3 runs)

2. SM Cylinder #CC 214, Used October 13 - November 9, 1976:

Date of Analysis	SM Value	LEC Value	% Difference	% Precision
10/10/76	39.1 ppm	38.5 ppm	1.60	Single Run
03/14/77	39.1 ppm	38.7 ppm**	-1.07	1.56 (3 runs)

3. Scott Marrin SO_2 Cylinder #CC 218, Used November 18 - December 9, 1976:

Date of Analysis	SM Value	LEC Value	% Difference	% Precision
10/10/76	39.2 ppm	38.47 ppm	-1.85	Single Run
03/18/77	39.2 ppm	40.7**ppm	-3.65	1.90 (3 runs)

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* Lockheed Electronics Corporation.

**Value used for calibration purposes.